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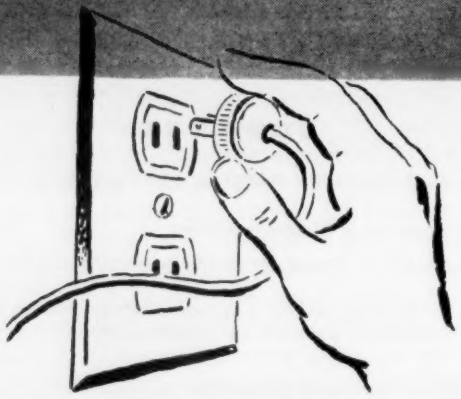

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Vol. 240 SEPTEMBER, 1945 No. 3

MERCURY FULMINATE, ITS AUTOCATALYTIC REACTIONS AND THEIR RELATION TO DETONATION

BY

LEROY R. CARL.

Nobel's fame is often ascribed to the invention of dynamite. This is unjust, because dynamite is only one of many high explosives, none of which could have been used without the vastly more important discovery of detonation and a method of readily producing it. Nobel was undoubtedly a very practical man but, nevertheless, he must have instinctively known the nature of explosives to have successfully invented so many of them for specific purposes. Sohlman and Schuck (1) quote Will as follows: "It was only this invention (in which the fulminate of mercury is used as a detonating charge for nitroglycerine and guncotton) that made it possible to use these substances for explosive purposes, while it is also due entirely to this invention that we have been able to discover and exploit the explosive properties of a whole series of other substances."

We see, then, that Nobel's invention (2) of the blasting cap (which is shown in diagrammatic sketch in Plate No. 1) in which mercury fulminate was used for the detonation of nitroglycerine was the primary step toward the development of the high explosives industry. This compound was for many years the only agency used to detonate high explosives. Stettbacher (3) as lately as 1925 says: "The old fulminate of mercury still claims its monopoly in this field."

Plate No. 2 shows large crystals of mercury fulminate magnified by 70 diameters.

As an illustration of the amount of interest which this compound has aroused and the amount of work that has been expended in the determination of the facts in connection with this compound the fact is cited that the number of references to mercury fulminate in a recent

(Note—The Franklin Institute is not responsible for the statements and opinions advanced by contributors in the JOURNAL.)

treatise on explosives was found to be greater than to any other subject or compound (4). Much careful work has also been done in which mercury fulminate has been used as a standard of comparison. Its value in that field will become more apparent as this paper approaches completion.

The terms high explosive and detonation are specific and belong to each other. If a material is a high explosive it can be made to detonate. If a material can be made to detonate it is a high explosive. Detonation is a comparatively recently discovered phenomenon (5) which many still do not recognize as a new phenomenon, but insist on treating as some sort of variation of chemical action.

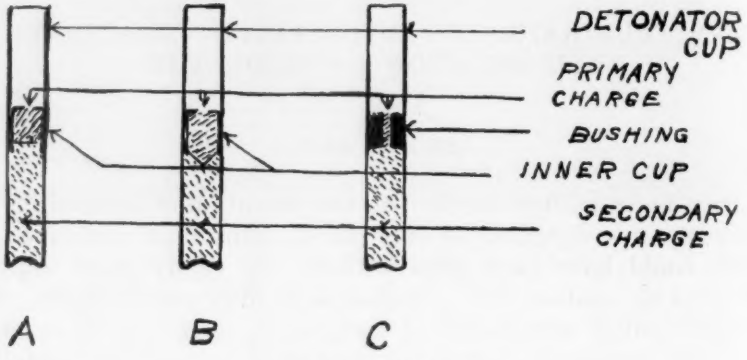

PLATE NO. 1.

The writer, however, has found that the facts of detonation cannot be explained by any conventional theories and has, therefore, after many years of observation devised a new theory (6) which has not been refuted in any way. This paper will make use of the new theory to explain facts which even the boldest have admitted were confusing and often contradictory.

The writer is well aware of the fact that mercury fulminate has been superseded as an initiating compound by others which have some superior qualities and that the compound is of theoretical interest only. However, it seems necessary that someone should write "a prologue to the epitaph" * of this imperfect thing which has been the first tool of the entrepreneur throughout the greatest period of industrial development that has ever been known and without which tool—the key to the use of high explosives—it is doubtful if that industrial development could have occurred.

I have said "this imperfect thing"; a better term would be this never perfected thing, because it is believed that most of the unsatisfactory characteristics of the compound are not inherent but are caused by the naturally occurring impurities, which curiously enough were

* With apologies to Elinor Wylie.

probably the reason for the early discovery and use of the compound and were also the reason for the discontinuance of that use.

A completely pure compound is practically not attainable. However, most compounds may be considered pure when the impurities which they contain have little or no effect on their properties. This is not true when the impurity is a catalytic agent for the formation or decomposition of the compound. Evidence will be presented in this

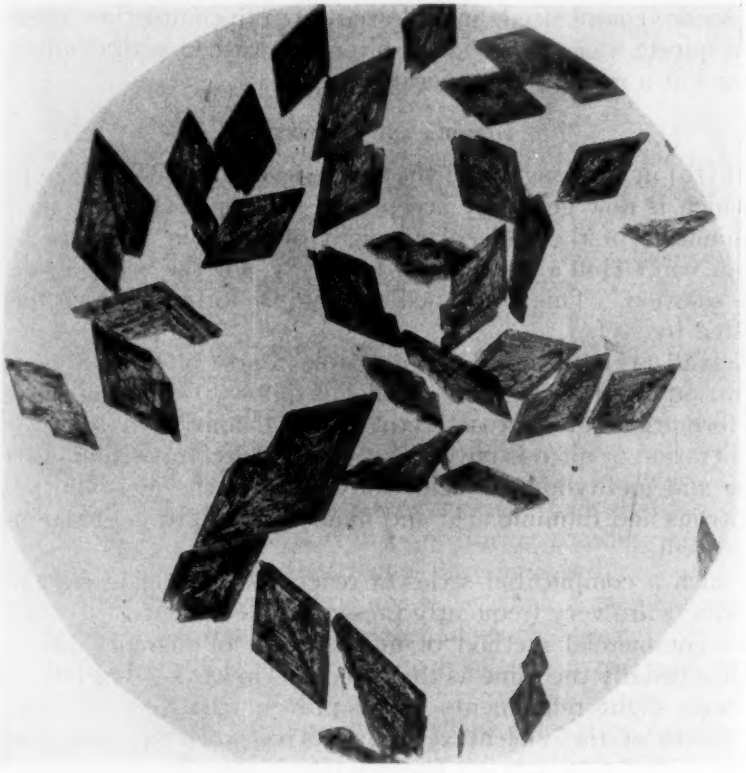

PLATE NO. 2.

paper to show that mercury fulminate has never been produced in a complete state of purity and that the impurity contains a catalyst for its production and decomposition.

According to Davis (7) mercury fulminate appears to have been first prepared by Johann Kunckel Von Löwenstern (1630–1703). This would date the discovery considerably before the beginning of chemistry as a science (8). An interpreted by Davis it seems that Kunckel had noted that mercury nitrate would react with alcohol but that the silver salt does not react under the same conditions. This comment is significant to this thesis and will become more apparent as we proceed.

Kunckel according to his Laboratorium Chymicum (7) dissolved mercury in nitric acid, evaporated the solution to dryness and poured alcohol over the residue. When this mixture was warmed slightly the reaction became vigorous.

The discovery, however, is usually ascribed to Howard (9) who also determined a number of its properties. Howard dissolved mercury in an excess of nitric acid and added the solution of mercuric nitrate and nitric acid to 95 per cent. alcohol. The mixture was warmed until effervescence commenced, and allowed to go to completion, after which the precipitate was collected on a filter and washed with distilled water and dried at a moderate temperature.

FORMULA AND THEORETICAL.

Nef (10) in 1894 suggested the simple formula C:N O H for fulminic acid which is now generally accepted. Wohler (11) made an indirect determination of the molecular weight of fulminic acid based on the value of van't Hoff's dissociation factor "i" for the sodium salt in 0.2 to 0.1 solution. This confirmed the simple formula which had been suggested by Nef.

Wieland (12) suggested the probable course of the reaction in the preparation of fulminate from alcohol as follows: Oxidation to acetaldehyde, formation of isonitroso-acetaldehyde, oxidation to isonitrosoacetic acid, nitration to nitro-isonitroso-acetic acid, decomposition into carbon dioxide and methylnitrolic acid, conversion of the methylnitrolic acid into nitrous and fulminic acid and finally precipitation of the insoluble mercury salt.

In such a complicated series of reactions many side reactions and by-products are very frequently present.

The commercial method of manufacture of mercury fulminate is still substantially the same as that used by Howard. The only changes have been slight refinements which prevent the loss of some of the by-products of the violent reaction. The procedure has practically become a ritual (see note). The reaction is completed in about twenty minutes. The product is gray or brown crystals, which usually have a purity of 98.5. Government and commercial specifications require a fulminate content of at least 98 per cent. These specifications have been written so that this method of manufacture could produce acceptable material. This crude product contains among other impurities a small amount of free mercury. This is the autocatalytic formation of mercury fulminate.

It is not the purpose of this paper to cast aspersions at the accomplishments of our great industrial and government research organizations, but rather to try to define the nature of detonation; however, one can

NOTE: "If the nitric acid solution of mercury is stood and the alcohol added to it (with warming) the fulminate is not the product." Cowper, *Trans. Chem. Soc.*, 1881, **39**, 242.

hardly refrain from comment at the lack of improvement in the method of manufacture and the quality of the product of such a vital and dangerous compound throughout the entire period of the chemical age.

It is a fact that an average high school boy with 15 minutes instruction and an average laboratory period of time could easily produce mercury fulminate of at least as good quality as has ever been produced anywhere or at any time.

However, the knowledge of this imperfect material with its radical differences in action from otherwise very similar compounds may serve a valuable cause, if by study of it in comparison to the others we learn something of the nature of detonation.

The writer attempted to produce a pure mercury fulminate by the use of pure reagent chemicals. Instead of dissolving the mercury metal in nitric acid, a C.P. mercuric nitrate was used. The proportions of the reagents were calculated so that the same relative amount of each ingredient was used as in the regular method of production. After the addition of the mercuric nitrate-nitric acid solution to the alcohol no reaction could be detected at once. The container was covered and allowed to stand for ten days, after which there was still no reaction. After the ten day period the container was warmed in a water bath and held at a temperature of 60° C. After approximately three days at the elevated temperature a rapid reaction developed which resulted in the production of a gray mercury fulminate. It is believed that the reason no reaction took place at once was the fact that no catalyst was present. It is probable that after or during standing several days at an elevated temperature, the alcohol may have reduced a portion of the mercuric nitrate to mercuric oxide or that a slight amount of mercuric oxide or of some other material which is a catalyst for the reaction found its way into the system resulting in the production of the usual impure product.

Taylor and Buxton (13) produced silver fulminate by dissolving metallic silver in nitric acid and adding the acid solution to alcohol. They say: "All of the precipitates obtained were composed of fine crystals, even when the temperature was kept so low that it took 2 hours to complete the reaction. It is better, however, to have the conditions such that the reaction will be completed in 15 minutes." They also say that a temperature of at least 60° C. was necessary for the reaction.

Taylor and Rinkenbach (14) also produced silver fulminate but instead of using the silver metal they used silver nitrate as one of the starting materials. They found that when the temperature was raised to 80° or 90° C. the usual product was formed. When the temperature was below 30° C. no product was formed after standing for three weeks even though the solution was seeded. At 30° to 34° C. a slight precipi-

tate was formed in 24 hours, but there was only a small yield after a month.

It seems desirable at this point to summarize the various experiences in the manufacture of mercury and silver fulminate, in an attempt to isolate the causes of the unusual results. Kunckel is said to have stated that mercury alone or with silver produced fulminate but silver alone did not. The method of Howard and the commercial method which make use of metallic mercury will start at room temperature and proceed with ever increasing violence until the reaction is completed in about twenty minutes. Taylor and Buxton were able to produce silver fulminate using a temperature of about 60° C. Taylor and Rinkenbach also made silver fulminate but they started with silver nitrate rather than the metallic silver as one of the starting materials. They found that a higher temperature was required in order to secure the usual product than was necessary when the silver metal was used. At a temperature slightly above 30° C. the reaction was very slow. It will be noted that mercury metal caused the most rapid reaction, silver metal somewhat slower and the refined salts the slowest reaction.

TABLE I.

Approx. Purity of Raw Materials, Per Cent.	Purity of Product, Per Cent.	Number of Batches Considered	Yield, Per Cent.	Amount of Product Required to Detonate Tetryl, Grams	No. of Batches Requiring More than 0.27 Gm. for Tetryl
98.50 Crude	99.59	32	74.4	0.255	13
99.59	99.75	5	84.0	0.240	1

It is well known that the metals which form two complete series of compounds are the most active as catalytic agents. Three such metals are mercury, copper and thallium. Metallic silver may be contaminated with either mercury or copper or both. The mercury metal, of course, will supply its own catalyst. The significance of the catalytic quality in thallium will become apparent later in this paper.

The writer observed an attempt to produce a pure mercury fulminate by the recrystallization of the crude material. The crude material was dissolved in aqua ammonia and precipitated out of the solution by neutralizing with dilute nitric acid. A total of 48 batches were run but for this study only 37 will be used. The other batches are not included because the process had not yet been standardized and those batches would not be representative of the general procedure. Thirty-two of the batches described here were a recrystallization of crude fulminate of specification quality. The remaining five batches were a recrystallization of the product of other batches. That is to say these five batches were subjected to a double refining process.

A study of Table 1 shows that even the material which has received the double refinement is still not entirely pure. The table also shows

that the material which has had the double refinement is somewhat more effective to detonate tetryl. But most important to this study is the higher yield secured. It is known that the fulminate decomposes very rapidly while in solution. The reduction of one per cent. in the impurity of the starting material caused an increase of nearly ten per cent. in the amount of material recovered from the solution. This is a case of the autocatalytic decomposition of mercury fulminate while in solution.

Many studies of the decomposition of mercury fulminate have been made at temperatures of 35° C. to temperatures high enough to cause almost instantaneous decomposition. Langhans (15) says that both gray and white fulminates are converted into a non-explosive substance (pyrofulmin) by heating for 100 hrs. at 90° C. in the wet or dry condition. A gradual rise in the mercury content of the fulminate from 70.42 to 76.6 per cent. occurs. The loss of weight is said to be due to the loss of carbon and oxygen. The substance pyrofulmin retains the original crystalline form of the mercury fulminate. He says: "These reactions are not conclusive, but point to pyrofulmin as being a mixture of mercury oxycyanide (Hg(OCN)CN) with some mercuric oxide." The accepted formula with mercury directly connected to oxygen could explain the presence of mercuric oxide.

TABLE 2.

Time of Storage, Months	Conditions under Which the Material Was Stored							
	Loaded at 3,000 psi		Loaded at 6,500 psi		No Treatment as Received		Pressed at 10,000 psi *	
	Fulminate		Fulminate		Fulminate		Fulminate	
	Content	Loss	Content	Loss	Content	Loss	Content	Loss
0	98.7		98.7		98.7		98.7	
4	98.0	0.7	97.3	1.4	98.7		96.2	2.5
6	97.2	0.8	96.6	0.7	98.7		96.1	0.1
8	95.1	2.1	94.7	1.9	97.4	1.3	94.1	2.0
10	92.8	2.3	91.2	3.5	94.9	2.5	90.8	3.3

* This material was pressed into a detonator capsule and then removed and stored in the loose condition.

Table 2 shows the results of storing mercury fulminate at 50° C. for ten months under several different conditions. The nature of the changes are indicated by the percentage of fulminate contained in the samples after the various periods as determined by chemical analysis. Changes not represented by fulminate content will be discussed.

Davis (16) discussing the deterioration of mercury fulminate when stored at elevated temperatures says: "At 35° C. it becomes completely inert after about three years, at 50° C. after about 10 months." The writer's experience is that when the fulminate content is reduced to

about 93 per cent. the material is no longer effective to initiate detonation in the commonly used high explosives and that it reaches this state of decomposition after about 9 months at 50° C. or after about 10 days at 80° C.

The rate of decomposition increases with increase of impurity as well as with increase of temperature. Both rates may be expressed as exponential factors. None of these rates can be taken as exact because every variation of the conditions has an effect. A study of Table 2 will confirm this fact. Rideal and Taylor (17) speaking of the rate of reaction of catalyzed reactions say: "The effect of temperature is usually exponential, the velocity constant more than doubling itself for a 10 degree rise. . . ." Other authorities will be quoted later in this paper showing that the reactions of mercury fulminate correspond to those described as catalyzed reactions.

Study of Table 2 also shows that when the fulminate was not pressed at all no decomposition could be detected by chemical analysis until after six months of storage. However, sensitiveness tests by the impact of a firing pin showed that the material became more sensitive with time of storage. The original requirement was a drop of 8 inches. After six months a drop of the same weight of 2 inches was sufficient to cause explosion.

One may say that sensitiveness is the essence of an explosive. It is the quality that must be understood if we expect to handle them with safety. Nevertheless, this very sensitive and dangerous explosive may become very much more sensitive merely by being held at a certain temperature. The writer recalls one batch of fulminate which exploded three different times without any apparent cause. A thorough investigation of the history of this batch failed to provide even a good guess as to the cause of the unprovoked explosions. Attempts were also made to cause explosions by simulating the conditions under which the accidental explosions occurred. This also was without success. Such experiences show that we know very little of sensitiveness and, therefore, very little about high explosives and detonation.

A further study of Table 2 shows that of those samples stored in the loaded condition the ones loaded at the higher loading pressure decompose more rapidly. The samples which were pressed into detonator cups and then removed from the detonator cups and stored in the loose condition show a puzzling manner of decomposition. There is a rapid decomposition at first followed by a slowing-up and then a resumption of the increase in rate of decomposition corresponding to the increased amount of decomposition products. The differences in rates of decomposition noted in this paragraph can be ascribed to the physical treatment to which the fulminate has been subjected. It seems evident that every stress which is applied to the crystal has its effect on the rate of decomposition. Joffe (18) discussing such effects

says: "Each stress exerts an influence that dies away very slowly. In a given state we meet traces of stresses which ceased a long time back, but remnants of which are still active at the present."

Consideration of the effect of stresses on the rate of decomposition influenced the writer to make some experiments in which the fulminate was subjected to a maintained pressure at elevated temperatures. This work was finally accomplished by the use of weighed springs. Blasting caps were loaded with approximately 0.5 Gm. of the fulminate and pressed at approximately 2,500 lbs. per Sq. inch. This was the first procedure for all samples. After loading the pressures were maintained by clamping the whole device in a carpenter's vise. This arrangement was then stored in an improvised wooden oven and heated by an electric light bulb. Table 3 shows the pertinent data. It will

TABLE 3.

Time. *Min.*	Maintained Pressure			
	2500 Psi Temp. ° C.	1500 Psi Temp. ° C.	1000 Psi Temp. ° C.	None Temp. ° C.
0	20	20	20	20
30	60	66	69	60
60	81	86	87	80
90	93	99	97	95
120	102	109	106	104
150	109 Expl.	115 Expl.	112 Expl.	110
180	165 Min.	177 Min.	167 Min.	110
210				112
240				113
270				113 No Expl.

be noted that in every trial in which pressure was maintained the samples exploded after about two and a half hours. The electric light bulb which supplied the heat was not broken in any of the trials although it was protected only by a thin wooden baffle and was only about three inches from the sample. These results merely confirm others that have been discussed. The explosions which occurred were not detonation but rather very rapid autocatalytic decomposition.

It will be noted that a maintained pressure in every instance caused an increased rate of decomposition, not only in comparison to the sample heated in the same apparatus but also in comparison to the rates of decomposition given in Table 2. These experiments add some weight to the contention that mechanical energy can be directly transformed into chemical energy.

We have seen that mercury fulminate decomposes at 50° C. at such a rate that after about nine months it is no longer effective to initiate the detonation of tetryl. And that after ten days at 80° C. it reaches the same condition. A little calculation from these figures will show that for every ten degrees increase in temperature the time may be

divided by three. Table 4 has been constructed by that method. Column (1) is based on the figures given above. Column (2) has been calculated in the same way except that the time found for decomposition to the completely inert condition is used, which was reported by Langhans as 100 hours at 90° C. Kast and Haid (19) determined the temperature of explosion by holding the explosives at a constant temperature and recording the time which elapsed before explosion. This method naturally cannot make a correction for the time required for

TABLE 4.

Temp. ° C.	(1) Time to Cause Failures	(2) Time to Become Inert	(3) Elapsed Time to Explosion
50	6480 Hrs.*		
80	240 Hrs.*		
90	80 Hrs.	100 Hrs.*	
100	26.6 Hrs.	33.3 Hrs.	
110	8.9 Hrs.	11.1 Hrs.	
120	178 Min.	222 Min.	
130	59 Min.	74 Min.	
140	20 Min.	25 Min.	
145			480, 331 Sec.*
150	400 Sec.	500 Sec.	275, 255 Sec.*
155			135, 165 Sec.*
160	133 Sec.	166 Sec.	64, 85 Sec.*
170	44 Sec.	55 Sec.	40, 35 Sec.*
180	14.6 Sec.	18 Sec.	15, 13 Sec.*
190	4.9 Sec.	6 Sec.	10, 8 Sec.*
195			8, 7 Sec.*
200	1.6 Sec.	2 Sec.	7, 8 Sec.*
205			5, 5 Sec.*
210	0.5 Sec.	0.66 Sec.	1, 3 Sec.*
215			0, 0 Sec.*
220	0.17 Sec.	0.22 Sec.	

* Experimentally determined.

the explosive to attain the temperature of the container. However, such a correction would cause very little change in the figures, except at the highest temperatures and when the time is very short. Column (3) lists the figures secured by Kast and Haid which are in duplicate.

A study of the times determined by the three methods as tabulated in Table 4 shows that there is remarkable agreement. At 170° and 180° C. the extrapolated figures given in columns (1) and (2) are so nearly equal to the experimental figures given in column (3) that an interchange would in no way change the picture. At temperatures higher than 180° C. the figures in column (3) tend to become greater than those in the other two columns. This is also as one would expect for the reason that a correction cannot be made for the time required for the explosive to reach the temperature of the container in the experimental procedure.

In order to show that the other initiators do not decompose at such a wide range of temperatures the results of three other com-

pounds are given from the work of Kast and Haid. These are given in Table 5.

The real value of all of these comparisons is to show that the explosion temperature is nothing more than the same thermal decomposition which occurs at all temperatures. The presence of the catalyst is the cause of the continuous increase in the speed of the reaction. The very rapid thermal decomposition is not detonation. In fact, the rapid chemical reaction acts to prevent the development of detonation. We may say that the presence of the catalyst makes it easier for the energy

TABLE 5.

Explosive	Temperature ° C.	Elapsed Time, Sec.	
Cyanuric triazide	200	40	2
	205	0	0
Lead styphnate	250	90	85
	265	65	45
	270	0	
Lead azide	335	12	9
	340	5	7
	345	7	6
	350	4	5
	355	0	

of the compound to be released in a less violent manner than by detonation. Quoting from Schwab (20), "Let us visualize our reaction system as having to pass over an 'energy hill' of height 'Q' before chemical change can occur. The catalyst can be imagined as an experienced guide under whose leadership a path is found leading into the opposite valley, without it being necessary to climb the whole of the height 'Q'."

Taylor and Munroe (21) and Storm (22) found that mercury fulminate that had been loaded into detonator cups at a loading pressure of 10,500 lbs. per sq. in. would not detonate, but merely burned without bursting the cups when ignited by the flash of a black powder fuse. Muraour (23) published similar findings. He says: "In the manufacture of detonators with fulminate at extremely high loading pressures (above 700 Kg./Cm.^{2}) (approximately 9,960 lbs. per Sq. in.) ignition by the flame of a Bickford fuse does not cause detonation. . . . Furthermore, the explosive so *dead pressed* is more susceptible to normal detonation if an explosive wave is started by the detonation of a small amount of an initiating explosive, such as lead azide." Andreev (24) has also become aware of this fact. He has tried to explain the action by the fact that the spaces between the crystals have become smaller so that the hot gases do not penetrate into the charge readily and thereby bring the material to the temperature of detonation.

It is worth while to note that Muraour states that the so-called dead pressed explosive may be detonated by a small amount of lead azide. It is also true that the detonation can be produced by a small amount of mercury fulminate loaded at a lower pressure.

The Dupres (25) tested the efficiency of detonators by observing the depression in a steel plate caused by the explosion of the detonator. The detonator was fired by the impact of a ½ lb. steel ball on a firing pin. They observed that the results were variable and often low when the charge had been subjected to a pressure of over 2,000 lbs. on a surface 0.25 inch in diameter. The pressure used, then, was approximately 40,000 lbs. per Sq. in. The writer's experience is that some failures * are encountered when pressures of 30,000 are used but that at 20,000 lbs. per Sq. in. no failures were encountered when fired by means of the impact of a firing pin.

The term *dead pressed* is, therefore, rather confusing for the material has not lost its ability to detonate in the strictest sense. What it has lost is the quality of an initiator when heat is applied. When impact of a firing pin or the impact caused by the detonation of another explosive is applied it detonated readily. The fulminate has become somewhat less sensitive to breaking or detonation due to the mutual support of the crystals. A force more effective for breaking than heat (impact or shock) will cause detonation.

The fact that the subject of dead pressing has excited so much interest and has been commented on by so many authorities makes the phenomenon worth an extended discussion with the hope that it may be disposed of finally. Mercury fulminate is an impure explosive which under certain favorable conditions will detonate. The fact that its manufacture could be accomplished by those who knew nothing of chemistry as a science shows it to be a crude material. The crude raw materials made the formation of the product possible. The impurities in the raw material increased and remained in the product. The same impurity or catalyst which made the formation easy also makes the decomposition easy. Any condition which tends to make mercury fulminate less sensitive to detonation allows a greater amount of the material to decompose by the catalytic action.

It is generally recognized that increased density causes all explosives to become less sensitive. This characteristic is more noticeable with mercury fulminate because of its tendency to decompose thermally, which in turn is due to the impurity which it contains. Commercial mercury fulminate must contain at least 98 per cent. fulminate. Now let us, for example, take a sample which contains only 93 per cent. Such a material will decompose thermally much more rapidly than the more pure sample, and if rapid thermal decomposition were detonation it would be more effective. But the thermal decomposition tends to

* This refers to failures to cause detonation of tetryl.

prevent detonation and, therefore, the sample containing only 93 per cent. fulminate could be said to be dead pressed at loading pressures much less than the 10,000 lbs. per Sq. inch which is that usually said to produce the condition. And to say it in another way, if we were to use only 0.15 Gm. of mercury fulminate of specification quality it would still be dead pressed at any loading pressure that we might select, as far as its ability to initiate tetryl is concerned.

The results of many experiments have been published which show the minimum quantity of different primary detonating explosives required to detonate less sensitive secondary detonating explosives. This method is a very useful one for showing the effectiveness of the initiating compound and the sensitiveness of the secondary explosives. Such tests are carried out by loading the explosives in detonator cups as shown in sketch No. 1A. In order that the work of different investigators may not be considered as contradictory it is necessary that we understand that the weight of the primary charge is not the only nor even the most important consideration. Bain (26) has shown that the height or depth of the charge is the critical factor. He has succeeded in initiating charges of tetryl with only 0.065 Gm. of mercury fulminate by using a bushing inside the blasting cap. The inside diameter of the bushing was 0.10 inch. The height of charge was found to be the same as when a larger diameter was used. The set-up is illustrated in sketch No. 1C. The illustration B in the sketch shows the method of loading sometimes used by those who think that the area of contact between the explosives is important. This method will use the initiator more effectively because a lower weight of charge will provide the required height to initiate detonation. As further evidence that the height of charge is the governing factor results of tests carried out by different persons in different countries are cited. Wohler (27) found the quantity of silver fulminate required to initiate tetryl and TNT was 0.095 and 0.36 Gm. respectively. Taylor and Buxton (28) found for the same initiator the quantities 0.07 and 0.24 respectively. The inside diameter of the detonator cup used by Wöhler can be presumed to be that usually in use in Germany, that is 7.7 mm. (0.303 inches) while the one used by Taylor and Buxton had an inside diameter of 0.220 inches. Comparing these results it will readily be seen that the height of charge is remarkedly similar. Calculations show that if the difference in diameter of charge is considered the weights of charge check exactly in one case and are only 0.02 Gm. different in the other.

The fact that the depth of the charge is the critical consideration will become most apparent when comparisons are made between the effectiveness of mercury fulminate and other initiators in this paper.

Wohler and Martin (29) reported their results of determinations of the least amount of various azides and fulminates which is effective to cause detonation of a number of the well known secondary detonating

explosives. These results are shown in Table 6. Another table (Table 7) has been made from these figures simply by calculating the amounts required so that they could be expressed as percentages of the amount required for the most sensitive secondary explosive, that is, tetryl. The new table does not give any new information but only makes the facts of the first table more impressive.

TABLE 6.

Smallest Amount (Grams) Which Will Cause Detonation of.....	Tetryl	Picric Acid	Trinitro Toluene	Trinitro Anisol	Trinitro Xylene
Cadmium azide.....	0.01	0.02	0.04	0.10	—
Silver azide.....	0.02	0.035	0.07	0.26	0.25
Lead azide.....	0.025	0.025	0.09	0.28	—
Cuprous azide.....	0.025	0.045	0.095	0.375	0.40
Mercurous azide.....	0.045	0.075	0.145	0.55	0.50
Thallium azide.....	0.07	0.115	0.335	—	—
Silver fulminate.....	0.02	0.05	0.095	0.23	0.30
Cadmium fulminate.....	0.008	0.05	0.11	0.26	0.35
Copper fulminate.....	0.025	0.08	0.15	0.32	0.43
Mercury fulminate.....	0.29	0.30	0.36	0.37	0.40
Thallium fulminate.....	0.30	0.43	—	—	—

TABLE 7.

Smallest Amount (Grams) Which Will Cause Detonation of Tetryl		Percentage Increase Over Amount Required for Tetryl to Cause the Detonation of			
		Picric Acid	Trinitro Toluol	Trinitro Anisol	Trinitro Xylol
Cadmium azide.....	0.01	100	300	900	—
Silver azide.....	0.02	75	250	1,300	1,250
Lead azide.....	0.025	000	260	1,020	—
Cuprous azide.....	0.025	80	280	1,400	1,500
Mercurous azide.....	0.045	66	222	1,122	1,010
Thallium azide.....	0.07	64	378	—	—
Silver fulminate.....	0.02	150	375	1,050	1,400
Cadmium fulminate.....	0.008	525	1,275	3,150	4,275
Copper fulminate.....	0.025	220	500	1,180	1,620
Mercury fulminate.....	0.29	3	23	27	38
Thallium fulminate.....	0.30	43	—	—	—

A study of these tables shows that all of the initiators are very much more effective than mercury and thallium fulminate for the initiation of tetryl. That all of them except mercury fulminate require many times as large a quantity to initiate TNT as is required for tetryl. That for the initiation of trinitroxylene (the most insensitive secondary explosive) mercury fulminate is more effective than the majority of the others. It is worth notice that thallium fulminate is the only one in the list which is less efficient than the mercury compound. This is believed to be due to the fact that the oxides of thallium are catalytic agents.

Wohler and Martin also (30) determined the heat of explosion of a number of the fulminates and azides. These are shown in Table 8.

The heats of explosion are so nearly equal that no solution of the relative effectiveness of the compounds as initiators can be derived from a study of these figures.

TABLE 8.

Compound	Heat of Explosion, Cal./Gm.	Compound	Heat of Explosion, Cal./Gm.
Silver azide	452	Manganese azide	676
Lead azide	364	Calcium azide	625
Copper azide	582	Strontium azide	295
Mercury azide	266	Mercury fulminate	397
Cadmium azide	558	Silver fulminate	470
Thallium azide	232	Copper fulminate	508
Nickel azide	656	Thallium fulminate	223
Zinc azide	360	Cadmium fulminate	470

Now if we consider the effectiveness of all of the initiators in Table 6 for the more insensitive explosives and compare those figures with the heats of explosion given in Table 8 we find that the differences are reasonable. The variation of effectiveness could readily be ascribed to the factors cited by Carl (31) as the explanation of selective effectiveness. However, the difference of effectiveness to detonate tetryl is obviously affected by some other factor in the case of mercury and thallium fulminate. That other factor is undoubtedly the presence of a catalyst.

In the case of mercury fulminate as compared to cadmium azide the ratio of effectiveness is as one to twenty-nine. Such a discrepancy is obviously not due to inherent differences in the compounds. Their different action must be sought for in a different direction. The catalytic decomposition seems to furnish the answer. Let us try to visualize the sequence of causes and results. The surfaces of the crystals of the primary compound are suddenly heated. There will then be a temperature gradient from the point at which the heat was applied to other points farther from the source of the heat. In the ordinary course of things the application of a rather sudden increase of temperature to a crystal, especially if applied to one side only, would tend to cause the crystal to break. Such breaking would be the result of stresses produced within the crystal by the uneven increase of temperature. In support of the contention that stresses will be produced in the crystal Bragg (32) is quoted: "Cleavage, hardness, electrical conductivity, thermal conductivity and refractive index are all directional properties of the crystal." In the case of the crystals of the compounds which are not contaminated with an impurity which is a catalyst for their decomposition breaking undoubtedly occurs almost instantaneously. That is to say detonation occurs almost instantaneously. On the other hand when heat is applied to mercury fulminate the tendency to cause

the crystal to break is still active, but there is also a very rapid catalytic thermal decomposition which reduces the material to an inert condition before the temperature rise is great enough to cause breaking. The thermal decomposition acts as a safety valve to prevent the more violent type of decomposition.

It might be significant that the inert product (pyrofulmin) retains the crystalline form of mercury fulminate.

Returning to a further discussion of the sequence of events when mercury fulminate is subjected to an increased temperature it is well to note that if the material contains more than 93 per cent. fulminate the thermal decomposition will at some stage become so rapid that it will produce a shock of sufficient intensity to cause the remaining fulminate to detonate. In every case, however, in which detonation is produced in this way, a portion of the explosive is destroyed by the thermal decomposition and the amount so destroyed is *the* measure of the minimum charge required for initiation of detonation. General observation indicates that in an American type detonator cup that quantity is approximately 0.20 Gm.

Storm and Cope (33) made trials to determine the minimum quantity of mercury fulminate which would break a small glass test tube. The fulminate was caused to explode by the heat of a flame applied to the outside of the tube. The least amount required was found to be 0.05 Gm. to cause any breaking and the amount required to cause breaking in all of ten trials was 0.07 Gm. A similar test with lead azide revealed that 0.01 Gm. always completely shattered the tube and that even 0.001 Gm. always drove the bottom out of the tube.

The minimum quantity of these two materials required to "break" a glass tube parallels their effectiveness as initiators for the rather sensitive explosives better than any other indirect test known to the writer. The test shows that a breaking force is the effective force for the initiation of the detonation wave. It does not show that one is more powerful than the other when they decompose in the same way but that one (lead azide) detonates more instantaneously when heat is applied.

The superior initiating compounds are all very similar. They should have no known melting point. They should not be volatile. They should be pure so that no change occurs during a change of temperature. The temperature at which they break down violently should be rather high. The ideally sensitive compound to detonation must be stable to other manners of decomposition. This seems to be a paradox, but it is not. In any system a gentle type of decomposition will prevent a more violent type.

As an example, the properties of crude and purified ammonium nitrate are here briefly described. The melting point of the purified material is 169.6° C. The crude product may begin to decompose at a

comparatively low temperature and can scarcely be melted before decomposition begins. The purified salt is remarkably stable. Decomposition begins to show at 200° C. but it is not until a temperature of 230° or 240° C. is attained that gas is evolved vigorously.

I have marshalled the facts to show that the manufacture, decomposition, dead pressing and low effectiveness of mercury fulminate are all caused by a catalyst which is always present in this compound. And also that the catalyst is one of the products formed by its decomposition, and therefore, that all of the reactions are autocatalytic. A few references by authorities on catalysis will be cited to show that the reactions of this compound correspond with catalyzed reactions in general. Rideal and Taylor (34) say: "Occasionally the reaction as it develops gives rise to compounds which themselves accelerate the reaction. Such cases are examples of positive autocatalysis," and "Normally, the acceleration produced by a catalyst is proportional to the concentration of the agent present, as will be illustrated, etc." These two quotations fit the facts with regard to the reactions of mercury fulminate. Ipatieff (35) says: "Actually, the catalytic reaction . . . is reversible, and the same catalyst may also serve for the hydrogenation . . . as well as for the dehydrogenation." This supports the contention that the same catalyst can cause both the formation and decomposition of mercury fulminate.

There is considerable difference of opinion among the students of catalysis on the ability of a catalyst to intiate a reaction. Many hold the opinion that the catalyst can only accelerate a reaction already in progress. Nernst (36) evidently was observing catalyzed reactions when he made the following observations: "All experimental measurement has shown that the velocity with which a chemical system strives to reach its state of equilibrium increases enormously with the temperature. This appears to be a universal phenomenon: Its importance for the course of chemical change and its significance for the so-called 'stormy reactions' (detonations, explosions, etc.) is at once evident," and again roughly in the same words: "Those chemical systems which are far removed from the stable form usually change with an increase of temperature, when this sufficiently increases the velocity with which they tend to reach equilibrium. Thus consider the innumerable decompositions, charrings, detonations, etc., of organic compounds on heating or consider the combustibility of many compounds in oxygen, etc. In most of these cases heat only accelerates a reaction . . . whether a decomposition or a union which would really take place spontaneously, though perhaps only after thousands of years." Nernst is evidently of the school which believed that all reactions proceed at all temperatures. He evidently, also, believed that a rapid chemical reaction was detonation. The latter fact, at least, provided some good company for the others who were mystified.

In contrast to the opinion of Nernst regarding the regular increase in the rate of reaction of the catalyzed reaction it is instructing to review the findings of Lewis (37) concerning other types of reaction. He says: "Probably the majority of chemical reactions, even those which eventually lead to the evolution of large amounts of energy, require some initial excitation of the molecule, and it undoubtedly frequently happens that a system must be lifted far above its original energy level before it can fall into a still lower energy level."

Both of these views cannot be true. The statement of Lewis, however, is the result of later consideration of the subject, and is supported by a quotation by Schwab (38) as follows: "Cases are accumulating of reactions effected by catalysts, e.g., in technology or in the organism which do *not* appear to occur *at all* in the same substrate *without* the catalyst, and it has been suggested therefore that catalysts possess the ability to *produce new reactions*." This is the later opinion and is supported by the fact that new compounds of high purity are available at this time which were not at an earlier date.

At the time that Nernst was making his investigations many reactions, which are now known to require a catalyst, were thought to proceed of their own accord. This is especially true of reactions which do not proceed in the absence of water. Nernst is also mistaken when he repeatedly speaks of the "innumerable detonations of organic compounds." Those with experience know that compounds which detonate from the application of heat are very rare. In fact if it had not been for the genius of Nobel it is likely that we could still go to the local drug store and buy picric acid as an innocuous treatment for burns.

I can quote many who acknowledge inability to make a reasonable explanation of the action of initiators, but none who claim to have developed more than a tentative hypothesis. Storm and Cope (39) recite a number of more or less fantastic attempts at explanation. The writer will confine his quotations to four admissions of inability to find any general rule.

Wohler (40) states that the addition of chlorate gives a greater total energy but a lower velocity of detonation and similar views are expressed by Berthelot (41), these authorities being of the opinion that the velocity of detonation exerts the greatest influence on the efficiency of a detonating substance. One may judge the value of these opinions by the statement of Storm and Cope in the same paper that they have no knowledge of any comparison of the rate of detonation of mercury fulminate in the pure state and its admixtures with potassium chlorate. The writer has no knowledge of any such comparisons either at that date. Carl's (42) results were published at a much later date.

From Storm and Cope (43) again we quote: "The writers believe that the efficiency of detonating compositions in bringing about the complete detonation of secondary explosives depends on some property

or combination of properties that has not been successfully determined or measured."

And again from the same source we quote again: "The above comparison is in every respect favorable to mercury fulminate. However, practical tests of these two detonating substances have shown that mercury fulminate is much inferior to lead nitride (azide) as regards capacity for initiating the detonation of certain of the nitro-substitution compounds."

Stettbacher (44) speaking of work reported by Wohler (45) says: "In a later paper Wohler compares the different properties of these high explosive substances, such as sensitiveness, velocity of detonation, size of grain, density, temperature of explosion and igniting power, and from this he tried to formulate a criterion, without, however, succeeding in reducing these complicated confused phenomena to a general formula."

It is the opinion of the writer that Nobel (46) in his patent specifications has most precisely described the nature of the initiating force in the following words: "The principle of its action consists invariably in the production of a very intense shock or pressure."

At this point it seems apropos to quote from an address given by DuPont (47) in commemoration of Lavoisier, the father of chemistry. Speaking of the time when Lavoisier was a young man (one hundred and seventy-five years ago) DuPont says: "It (chemistry) was a hodge-podge of mysticism and magic. . . . This was not for any lack of facts. . . . No, there were plenty of chemical facts. However, no one understood them either individually or in their relation to each other."

The writer is convinced that the statements made in the preceding paragraph in regard to chemistry when Lavoisier was a young man could be applied to the state of knowledge of high explosives and detonation today. There are in this case, also, plenty of facts. The relation of the facts to each other and to the facts in other branches of science are not understood either. In the writer's opinion the understanding of facts and their relation to each other is what constitutes theory. Buckingham (48) has offered a picturesque definition of theories. He says: "Theories are probably to be regarded as indispensable sign-posts in what would otherwise be a dark forest of facts."

And it might be added that when one of these theories shows us where we are in the forest or even lead us out of the forest, the group of facts is, then, approaching the condition of a science.

SUMMATION.

Evidence has been presented to show:

1. That the production and decomposition of mercury fulminate are catalyzed reactions.

2. That the catalyzed reaction is the cause for the much reduced effectiveness of mercury fulminate as compared to similar compounds

when used to initiate detonation in the rather sensitive secondary detonating compounds.

3. That the rapid autocatalytic decomposition always causes a portion of the fulminate to be destroyed before detonation starts.

4. That when mercury fulminate achieves detonation, its power to initiate detonation is comparable to other similar compounds.

5. That when an increased temperature is applied to mercury fulminate a very rapidly increasing rate of reaction takes place, but no matter how rapid the reaction, it is not detonation.

6. That a rapid chemical reaction tends to prevent rather than to cause detonation.

7. That, although there has been a great accumulation of facts regarding mercury fulminate and high explosives, the accumulated facts do not in any way resemble a science.

8. That detonation is an entirely new phenomenon which cannot be solved except by the use of a new theory.

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Cotton for Insulation.—Because of the probability of large scale use of insulating material in post-war air conditioning and refrigeration, a committee of the U. S. Department of Agriculture now considering post-war programs has devoted special attention to cotton insulation. The committee's report on post-war prospects for cotton in domestic markets points out the high quality and convenient form of modern-style cotton insulation which has been made flame-resistant and water-repellent.

Of a dozen common insulating materials listed, cotton insulation has the best insulating value—that is, a standard volume lets the least heat pass in a given time. It is also the lightest. "The light weight of cotton," says the committee, "makes it an ideal insulator for such objects as refrigerator cars and trucks and for aircraft where weight is important." Labor costs for applying insulation in buildings are estimated to be 40 per cent. less for cotton insulation than for competing materials."

In a summary paragraph on insulation prospects the committee says: "The principal problem in getting cotton used for insulation is likely to be that of cost. Present estimates are that to meet competition, raw cotton would have to be obtained at approximately 8 cents a pound. . . . Cotton low middling and lower in grade with sound staple 13/16 inch and shorter is satisfactory. . . . Further mechanization of cotton production and harvesting in areas that normally produce short staple cotton may make it possible to provide such cotton for this use without adversely affecting the incomes of cotton growers. The extent to which cotton will be used for insulation at present price levels and without a subsidy will depend on the aggressiveness of the salesmanship of manufacturers and distributors in exploiting the superior advantages of cotton over competing materials."

R. H. O.

Windowless Boiler House Serves Chevrolet Forge Plant.—C. A. SPRINGER. (*Power*, Vol. 88, No. 10.) The Chevrolet aluminum forge plant at Saginaw, Mich., turns out aluminum forgings for airplane parts such as landing gears, and for engine parts such as crank case housings for Pratt & Whitney engines, with bulk of the output solid aluminum propeller blades of various sizes. Originally the plant was scheduled to produce almost four million pounds of aluminum forgings a month, but the operators have nearly doubled this figure with only incidental additional equipment.

Designed to operate in complete blackout for war time security, the boiler house serving this war plant is windowless. Light-trapping inlet louvres and roof ventilators provide ventilation. The louvres also supply large amounts of air for combustion, a total of about 200 tons per hour when boilers are operating at full load. The boiler house is completely automatic.

Four 4-drum bent-tube boilers, with sectionally supported air-cooled settings, supply steam for steam hammers, process work and space heating. Designed for 200 psi, the boilers operate at 175 psi, no superheat. Each boiler can produce 100,000 lb. of steam per hour with a higher peak possible for shorter periods. Boilers are fired by spreader stokers with traveling grate continuous ash discharge.

R. H. O.

ELECTRONICS AND DEVELOPMENT OF ELECTRONIC TUBES.

BY

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Since the discovery,—some 30 years ago,—of the remarkable properties of electron tubes, namely, of their capability to generate powerful oscillations of radio frequencies and to amplify the minutest a-c currents to a high level, the entire progress of radio art became inherently connected with the development and designing of electron tubes. This is why in everyday language the terms "electron tubes" and "radio tubes" have frequently been used as synonyms. Tremendous progress in non-radio applications of electron tubes during recent years brought about a widening of the scope of activities of many "radio" specialists who started calling themselves "electronics" engineers by which name one designates designers and users of electron tubes and associated circuits. Electronics engineers working in different branches of "Electronics" became more intimately interested in each other's problems to their mutual advantage. The following brief review of electronic tube development is made in accordance with this new tendency, that is, it covers not only radio, but all important types of electron tubes.

It may be of interest to note that the word, "Electronics" was first coined as the name of the well known McGraw-Hill technical periodical which made its appearance in April, 1930. However, even now there is no general agreement as to the exact meaning of this word. The closest definition of "Electronics" agreeing with its actual usage by the majority of specialists is perhaps the following: "Electronics is that branch of Physics and Electrical Engineering which deals with the phenomenon of conduction of electric currents through vacuum, gases and vapors, with their control, and their practical applications." In this place, it should perhaps also be reminded that the ancient Greek word "electron" meaning "bright" or "shining" was used to designate fossil amber, the first source of electricity known to present humanity since the 6th century B.C. through Thales of Miletus. In our era, in 1891, the same name was applied by G. Johnston Stoney to the smallest quantity of electricity, E, discernable in electro-chemical processes following Faraday's law of electro-chemical equivalents. Earlier, in 1874, he proposed this quantity, E, as one of the three basic "natural" units (velocity of light and gravitational constant being two other units). Stoney viewed his electrons as integral parts of and physically

not removable from atoms (1). Subsequently, in 1897, J. J. Thomson proved experimentally the independent existance of these minute charges of negative electricity or "corpuscles" detached from the rest of the ponderable matter and constituting electric current through an evacuated tube (2). Then, immediately, the name "electron" was generally applied to Thomson's corpuscles.

In spite of the fact that Electronics is the youngest branch of Electrical Engineering, the electronic tube is much older than usually assumed. In fact, since Otto Von Guericke's invention, 300 years ago, of his primitive vacuum pump and electrostatic friction machine,—both of which were being diligently improved by other experimentors,—scientists of the whole civilized world have been in a position to observe the colorful and entirely mysterious at that time phenomenon of electric discharge in evacuated vessels. Thus, professor Fr. Hawksbee demonstrated purple glow of electric discharge to his amazed audience in the Gersham College, England, in 1705–1706 (3). Hawksbee's experiments and, later on, Benjamin Franklin's momentous discovery of atmospheric electricity, also, the invention of the Leyden jar by Musshenbroek in Holland, and Kleist in Pomerania (about 1745) obviously prompted general interest in such experimentation. Indeed, we find a number of publications during the 1740's and 1750's describing experiments with electric discharge in air and *in vacuo*. On February 2, 1752, William Watson (4) aroused admiration by demonstrating before the Royal Society of London "the most delightful spectacle . . . of aurora borealis" produced by electric discharge through an evacuated 3-inch glass tube 3 feet long. An improved "air-pump" producing "perfect" vacuum (in fact, somewhat less than 1 mm pressure) was constructed for this purpose by Watson's assistant, Mr. Smeaton. Watson also demonstrated a discharge through a 30-inch "Torricelli vacuum" in a 0.3-inch *mercury tube* in which "electricity prevailed vacuum in a continued arch of lambent flame." During the same period, a number of scientists: L'Abbé Nollet in France, Bose in Germany, Musshenbroek in Holland, Benjamin Franklin in America, M. V. Lomonossoff and G. W. Richmann in Russia and many others devoted much of their time in trying to penetrate into mysteries of, what we now call, electronic discharge. Among later observers we find the great Faraday (5) who described results of his observations in his "Twelfth series of lectures" of the Royal Institution, 1838. But the actual scientific study of this remarkable phenomenon was begun only during the 1870's, inspired mainly by the rather fundamental work of Wilhelm Hittorf in Germany (6) and by the brilliant British scientist, William Crookes (7). This general study ultimately resulted not only in the development of modern Electronics with the whole line of modern electronic tubes, but brought about a revolutionary electron theory of matter and changed the entire philosophical background of science.

From the engineering viewpoint, the most important event for development of modern electronic tubes, after this development had been started, was the invention of the high-vacuum mercury "diffusion pump," 1913–1915, by Gaede in Germany (8) and by Langmuir (9) in this country, who improved Gaede's pump and built his "condensation" pump. The new pumps permitted the proper and rapid outgassing of parts in any kind of tubes and establishing, when necessary, real *high vacuum* in certain types of tubes playing the basic role in radio, also, now in many industrial applications.

The improved vacuum technics resulted also in a wider application of incandescent, or thermionic cathodes in electron tubes, which should be considered as another important factor in the general progress of modern electronics. These cathodes and their role in establishing discharge current had been studied since 1882 by many investigators: by Elster and Geitel (10), by Hittorf (11), by Goldstein (12), by Fleming (13), by Wehnelt (14) (the originator of the important type of oxide-coated cathode), and some others. Finally, a complete theory of thermionic emission from incandescent metals was given in the noted work of Richardson (15). However, practical application of such cathodes at any high voltages required by various electron tube services became feasible only with the inauguration of high-vacuum technics, as was first described by Coolidge (16).

EARLY ELECTRON BEAM TUBES.

An immediate outgrowth of universal scientific work with Crookes' tubes, also called Hittorf's discharge tubes, or else, Geissler's tubes was the invention in rapid succession of three important types of electron tubes: the Lenard tube (1894) (17), the Roentgen tube (1895) (18) and the Braun tube (1897) (19). All three types were, what we call, "soft" tubes, that is, partially evacuated; their electron mechanism in our present day terminology consisted of a "cathode ray" (20), a narrow electron beam issued from a concave "cold" cathode as a result of its bombardment by gas ions. Modern versions of all three types are high vacuum tubes with incandescent thermionic cathodes and special provision for focusing electrons, designed according to the rules of modern electron optics.

The most popular from the start was the *Roentgen* or the *X-ray tube*. In addition to its initial uses in surgery and medicine it has found wide application in modern industry for radiographic work. As mentioned before, high vacuum X-ray tube with an incandescent tungsten filament was first introduced by Coolidge in 1913. Among important modern developments one may mention the 1,000,000 volt tubes which are now in use in special therapy (21), also in industry for quality inspection of seam welds and castings in important machine parts (22). Another recent outstanding development in the X-ray tube field is a "cold

cathode" tube for *ultra-high speed radiography* designed by Slack and Ehrke (23). This tube permits taking X-ray pictures of very rapidly moving objects, such as bullets or shells in gun barrels. The instantaneous current, instead of being measured in fractions of an ampere as in conventional tubes, here reaches 2,000 amperes and is derived from a metal-vapor arc of short duration between two cold electrodes.

The *Lenard tube* or the high voltage cathode ray tube can be viewed as a sister-tube of the Roentgen tube as to its general construction, operating voltages and some of its applications. But instead of the production of X-rays, the Lenard tube is designed to permit high speed electrons to pass through an extremely thin window in the tube wall and to become available outside the tube for bombardment of various specimens. Although present applications of the Lenard tube are still limited to biological research, there are indications that it may be advantageously used for medical purposes, because of the greater physiological effects of the electrons than of the X-rays generated by an electron beam of equal power (24).

The Braun or the "Cathode ray" tube par excellence, with its fluorescent screen, invented by Ferdinand Braun in 1897, for almost 30 years had been used only in laboratories under the name of cathode-ray oscillograph for qualitative study of a-c or transient electrical phenomena. However, as early as in the first decade of this century Prof. Boris Rosing in Russia (25) and Mr. Campbell Swinton in England (26) anticipated the feasibility of the application of the Braun tube in television, because of practically inertia-less operation of the electron beam. This dream was realized 25 years later by Zworykin in his Kynescope (27) for reception of televised pictures. By further modification of the cathode ray tube and substituting a photosensitive for the fluorescent screen, several types of transmitting or "pick-up" tubes have been produced, such as the Image Dissector of Farnsworth (28), the Iconoscope (29) of Zworykin, etc.

Within the last few years the cathode ray tube has acquired quite a new importance in some extremely useful warfare applications, and it will undoubtedly be used in postwar time devices designed to increase safety of communication by air, sea and on dry land, both by railroads and highways.

Application of the cathode-ray tube to a variety of modern problems was enhanced by the early work of Johnson who in 1922 modernized the tube by the introduction of the incandescent "Wehnelt" cathode and by redesigning it for "low" voltage operation instead of the many thousands of volts of the original Braun tube (30). It is interesting to note that Wehnelt himself as far back as 1905 suggested similar improvements, but they could not be realized at that time because of poor vacuum technics resulting in extremely short life of the oxide cathode (31).

MERCURY VAPOR TUBES.

Another old type of industrial electronic tube is *the mercury arc rectifier*.

Electron discharge through mercury tubes, had been observed by scientists in England, France, Germany and Holland as far back as the 1750's. A closer scientific investigation of this phenomenon was carried out during the last two decades of the 19th century by several physicists, such as Jamin and Meneuvrier in France (32), Arons in Germany (33), etc. However, the rightful inventor of the mercury arc rectifier for alternating current as a useful engineering device was Cooper Hewitt (34) in this country, 1902. The invention was a result of his experimenting with mercury discharge lamps for illuminating purposes. Our domestic, also, the European literature of that time is full of enthusiastic descriptions of the "new" Cooper Hewitt device. From the very beginning the inventor conceived the single and multi-phase versions of the rectifier. The early applications of "glass" rectifiers was charging automobile storage batteries of electrically propelled cars, also, feeding d-c series street arc lamps from a-c mains (35). The "steel-tank" model necessary in high-power applications was also invented by Cooper-Hewitt. Some early experimental installations of this type were made by Frank Conrad in Pittsburgh factories and on a locomotive of the New York, New Haven and Hartford railroad, operated from an 11,000 volt overhead line (36).

The mercury rectifier at once aroused the live interest of men of vision, such as George Westinghouse and Steinmetz, who immediately undertook further development of the device. (Cooper Hewitt from the start joined with George Westinghouse for practical manufacturing of rectifiers.) However, it took from 20 to 30 years to make industry accept it, because, on one hand, electrical engineers would not easily part with their excellently developed rotary converters in the same type of service, and on the other hand, the *back-firing* inherent in mercury rectifiers represented a nuisance prejudicing industrialists against the new device; although considerably reduced, as the art progressed, and finally made almost negligible, internal arcing could never be completely eliminated. Important steps in the direction of improvement and reducing arcing-back were made by Bela Schafer of Frankfurt-on-the-Main, about 1911 (37). He designed tanks with better air-proof joints and introduced rectifier operation under *continual exhaust* which has since become standard practice with all steel tank rectifiers.

Another important step in the development of large mercury rectifiers was the introduction of *grid-control* accomplished by proper biasing of individual grids surrounding each anode in the tank. Although anticipated about 30 years ago (38), it did not become practicable until Toulon suggested (1924) controlling the output current and voltage by

phase shift of the a-c grid voltage with respect to the anode voltage (39). This represents the advantage of easy and precise controlling of the output power without expensive extraneous devices, such as induction regulators or specially designed multi-tap transformers.

The avowed advantage of the mercury arc rectifier is its extremely low internal voltage drop,—of the order of the ionization potential of

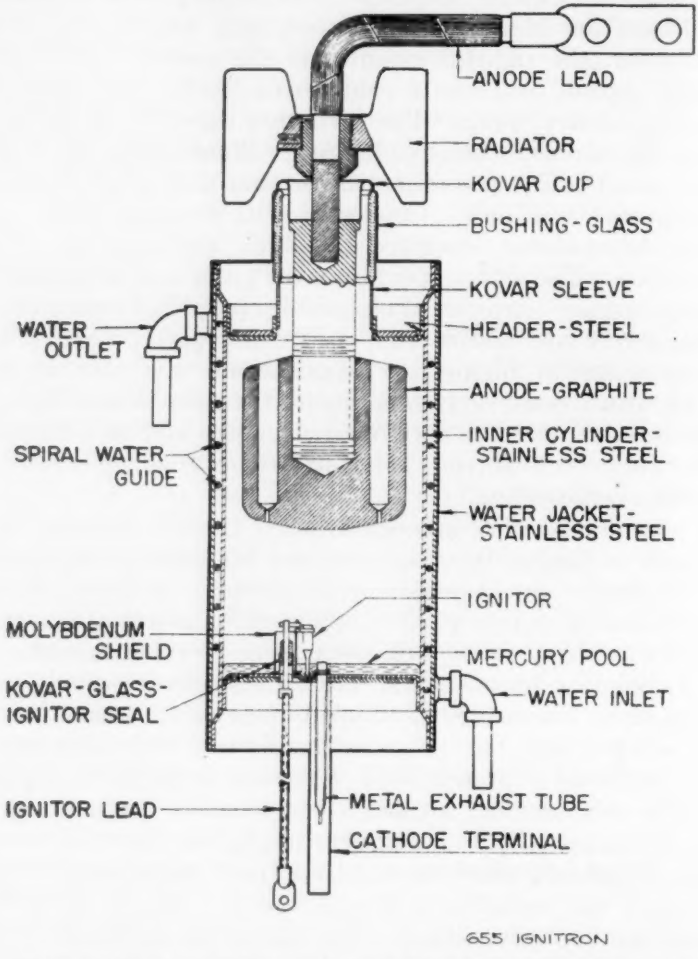

FIG. 1. Cross section of size D ignitron for 2400 kilovolt-amperes maximum demand and 14,400 amperes maximum peak current at 250 volts.

mercury,—independent of load, hence, high efficiency in operation. Together with almost unlimited supply of electrons by the mercury pool cathode, this makes the mercury rectifier suitable for feeding heavy duty d-c motors with variable load, such as in electrical railways and in certain types of factory installations. In addition, because of

its high current capacity, up to 10,000 and more amperes per unit, the mercury arc rectifier proved to be well suited for services in electrochemical industry.

All advantages of the ordinary and grid-controlled rectifiers are inherent in the newest type of industrial electronic tube, the *ignitron* which, in addition, possesses other valuable features. The ignitron (40) was invented by Slepian and Ludwig in 1932. In its modern version it is a *single-anode all-metal* mercury pool tube (Fig. 1). But, instead of the conventional mechanical starter of discharge and of the ever

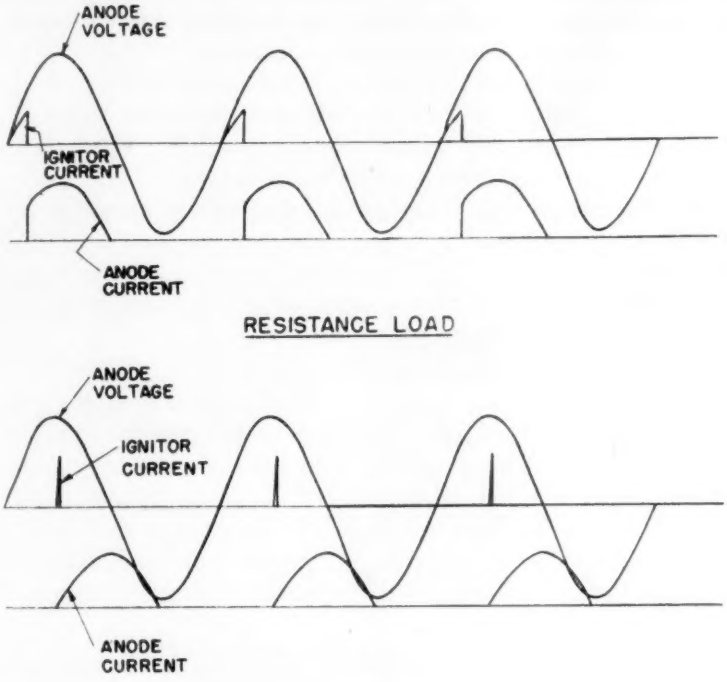

FIG. 2. Control of the Ignitron output current by firing the ignitor.

present auxiliary "keep-alive" arc enhancing internal arcing in the tube, the anode current is started during each cycle by the *ignitor*. This is a short rod of refractory material with a pointed tip projecting into the mercury pool. During each cycle sufficiently high current of extremely short duration is sent through the ignitor; it strikes an arc which is immediately transferred to the anode, while the ignitor current ceases (Fig. 2). Average output current and voltage can be easily controlled by shifting the phase of the ignitor current with respect to the anode voltage in a manner analogus to the Toulon grid-control.

A single-anode all-metal tube, such as the modern ignitron is, has definite advantages over large and bulky multi-anode tanks. First, it has a considerably smaller tendency toward internal arcing. Then, it lends itself to large scale production by modern methods, so that sealed-off ignitrons even for high ratings can easily be, and are, constructed, thus obviating from industrial installation vacuum systems necessary for operating multi-anode tanks. Also, being a smaller and lighter unit, the ignitron can be conveniently handled in the factory, in transportation and in the field. It can be employed in a single or multi-phase installation by combining as many tubes as necessary in several well known circuits. Finally, single anode tubes can be operated in

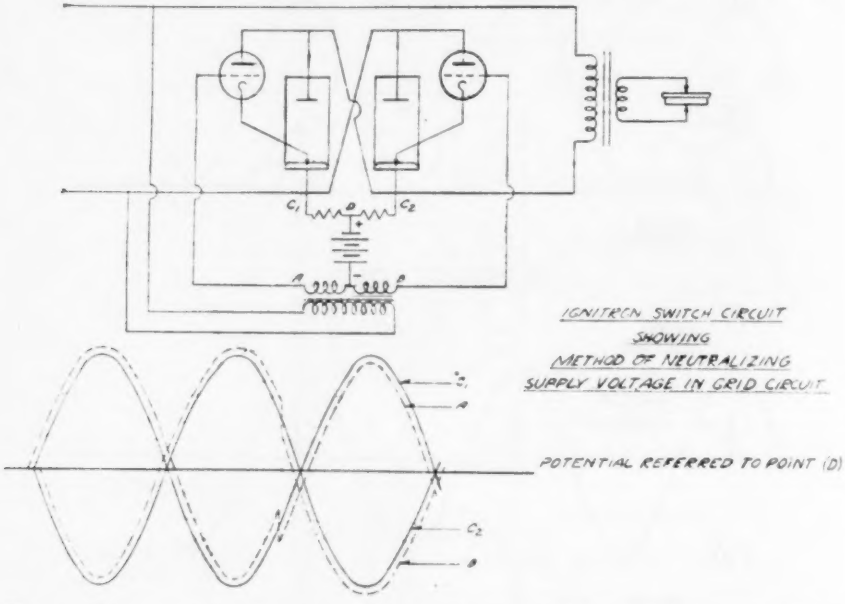

FIG. 3. Inverse-parallel connection of ignitrons, representing an ideal electron switch.

inveres-parallel connection (Fig. 3), thus realizing a perfectly controlled single-pole double-throw *electron switch* whose operation can be pre-determined with the precision of a small fraction of a cycle of the a-c power supply. This scheme is widely used in resistance welding, one of the most important modern processes in industry. In addition to this application, during recent years the single anode rectifiers have also been successfully adopted by the electro-chemical industry for rectification purposes with precision controlled output. Finally, the single-anode rectifiers are very suitable for "power inversion" by which one means transformation of d-c into a-c power, also for changing 60 cycle power supplied by the utility companies into 25 cycle power; the latter is sometimes used for more efficient operation of motors and other a-c power devices.

In quite recent times another type of a single-anode mercury pool tube was introduced in industry, the so-called *excitron* (41). It is a grid-controlled tube, and its performance apparently is as good as that of the ignitron; but its structure is somewhat more complicated, also, the ever-present keep-alive arc increases the probability of arcing back.

A very important member of the family of mercury vapor tubes is the *thyratron*. In its simplest form it is a vapor filled triode with a filamentary or indirectly heated cathode. Its idea was conceived 30 years ago, when attempts were made to use mercury vapor tubes in radio reception and transmission. But its practical application for industries purposes started only about 1928–1929 (42), suggested by Dr. A. W. Hull. There are both glass and all-metal types in use. Some of the modern types are filled with xenon or krypton gas rendering the operation more independent of the ambient temperature, but shortening tube life as compared with mercury vapor tubes. The thyratron is indispensable in modern industry where it is widely used for firing ignitrons in resistance welding circuits in which it permits the realization of an ideal electronic contactor effecting any predetermined sequence of operations with great precision. It also found application in precision regulation of generator voltages, speed of electric motors, temperature of furnaces, and many other control and regulation services. Finally, it is also used as a grid controlled rectifier in installations with relatively low power demand.

The simplest member of mercury vapor tubes is the *phanotron*, a mercury-vapor glass diode with oxide coated thermionic cathode. Within the last fifteen years it has supplanted the kenotron, the high vacuum electronic rectifier, in services such as supplying power to radio transmitters and receivers, because of greater efficiency and greater current ratings of tubes filled with mercury vapors.

HIGH-VACUUM RECTIFIERS OR KENOTRONS.

The high-vacuum rectifier or the *kenotron* was the first product of the greatly improved vacuum technics 30 years ago and of the new theory of pure electron discharge in high vacuum, promoted by Child (43), Langmuir (45), and Shottky (44). In modern industry, kenotrons survived only in high voltage devices in which emphasis is placed on high voltage rather than on high current; this is the case with X-ray installations, precipitrons, electron microscopes, etc.

HIGH-FREQUENCY TUBES.

The first electron tube ever used in high-frequency circuits was designed by Zehnder (46) in 1892, as an indicator of oscillations in his demonstrations of "Hertzian" waves to large audiences. The first vacuum tube detectors of radio waves were the noted Fleming *valve*

(47) and the Wehnelt tube (48), both proposed in 1904. The Fleming valve was an incandescent lamp with an additional electrode—the anode—and was the outgrowth of the Edison Effect recorded 20 years earlier. It may be noted that Edison embodied this "effect" in a patent for regulating current in electric lamp circuits; thus, in the light of our modern knowledge it can be viewed as the first attempt of "industrial" application of electronics. However, the extremely low sensitivity of the device, and general lack of proper understanding of the observed phenomenon at that time, prevented its early practical applications (49). The early diode detector could not successfully compete in practical applications with other contemporary non-electronic types of detectors (such as magnetic, electrolytic and crystal detectors), until its sensitiveness was increased many-fold by adding a control grid. This was accomplished by Lee De Forest in this country in his famous *audion* in 1907 (50), and soon afterwards by several inventors in other countries, each claiming the originality of invention. One hardly should wonder at this coincidence, as the effects of a grid on electrostatic fields has been known since the classical work of Maxwell. But one may really wonder at the fact that for almost 10 years the electron tube attracted but moderate attention from radio engineers. It was realized but slowly that a high vacuum three electrode tube could become a source of powerful CW oscillations of practically any frequency, or it could amplify weak oscillations to a high level. Then, it was christened by Langmuir, *pliotron* (51), from the Greek word *pleion*, "more," to designate that it might render more services than mere current rectification which is the basis of detection of radio waves. One of the first important application of the electron tube amplifier was in transcontinental telephone lines where it was employed as a "repeater," that is, as an amplifier of weak telephone currents (52). Very soon, experiments with the audion in radio transmitters led to the realization of the longed-for radio-telephony, which in 1920 brought about the great modern art of radio broadcasting.

Starting with tubes of only a few watts, radio-frequency output from larger electron tube oscillators grew rapidly to several hundred watts. Finally, with the development of glass-to-copper seals by Housekeeper (53) in 1922 water-cooled tubes with external copper-anodes could be designed for several kilowatt and even several hundred kilowatt ratings. Yet, the largest "transmitting" tubes in this country designed during the last 20 years were of not more than 100 kw rated output, with the exception of one or two quite recent types, while in Europe during the 1930's many tubes were in service with 350 and even more kilowatt ratings. This apparently strange condition is to be explained by the ceiling established in the United States for broadcast transmitters at 200 kw peak output which can easily be taken care of by two 100 kw tubes in standard circuits.

However, in recent times a number of large "radio" tubes has found application in industry in a variety of projects for "industrial" heating of metals and dielectrics. There are some industrial installations in which hundreds of kilowatts are employed in a single project. As a

FIG. 4. WL-895 R modern 100 kilowatt maximum rating tube for radio and industrial applications.

good example, one may mention *tin-reflowing* installations. The total h-f power generated in six or seven projects of this kind exceeds 2.5 times the total nominal output of all broadcast transmitters in the country. Each individual oscillator employs four 100 kw tubes of the 895 type shown in Fig. 4, and several oscillators are used in a single project.

The substitution of electroplating of iron sheets with subsequent tin-reflowing by h-f heating for the customary "hot dip" method not only gave about 60 per cent. saving in tin,—a critical war material,—but improved the quality of the product, considerably reduced shrinkage

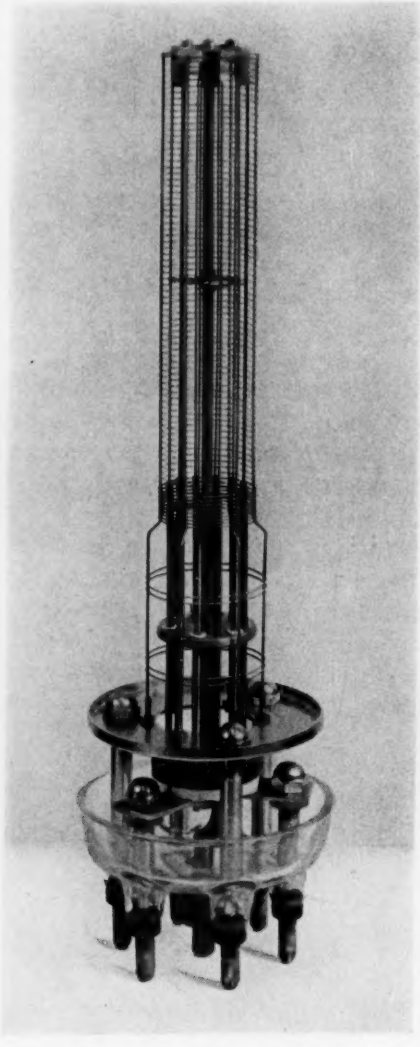

FIG. 5. Cathode-grid assembly of the 895 tube, supported from a moulded glass dish.

and permitted an increased rate of production within the same factory space. All necessary operations,—mechanical cleaning of iron strip, degreasing, rinsing, tin-plating, tin reflowing by high-frequency heating and even welding the beginning of the new roll to the tail of the preceeding one,—are performed on a long strip of iron moving with a speed of 1000 feet per minute (54).

There are other projects where h-f tubes are employed in industry, and their number may increase in post war time. Obviously, there is no longer a reason to limit output to 100 kw per tube. Also, there is no longer justification to call high-vacuum electronic tubes, "radio" tubes. It seems that instead of the customary classification, *receiving*

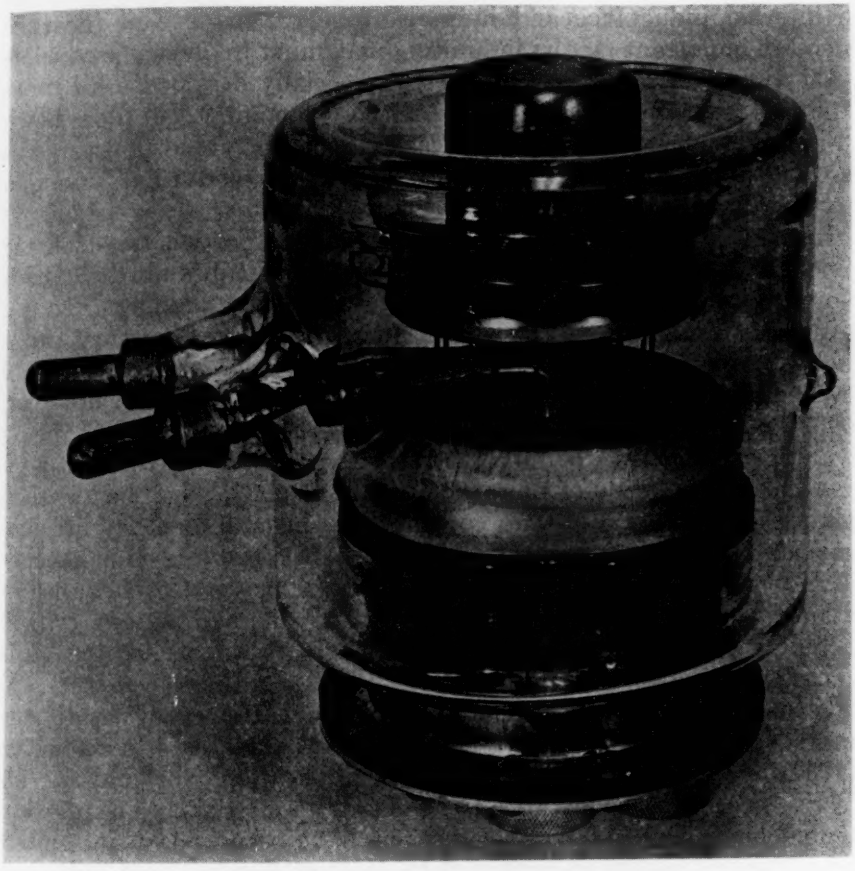

FIG. 6. WL-530 ultra-high-frequency triode for special applications. A water-cooled tube designed with heavy self-supporting bird-cage thoriated tungsten filament and 100 per cent. utilization of the anode surface.

and *transmitting* tubes, one should perhaps call them *small signal* with linear amplification and *power output* tubes in which power ratings are of prime importance; this designation will be applicable both to radio and industrial electron tubes.

ULTRA-HIGH FREQUENCY TUBES.

The advent of television, shortly after 1930, followed by the introduction of FM in the broadcast field made the radio world u-h-f minded.

High output tubes for frequency band from 40 to 100 MCS came in demand, and a few types were developed specially for this purpose. These tubes were designed along the same general lines as conventional triodes or tetrodes but, ordinarily, they were of a short squat structure with inverted copper-glass seals. Moulded glass dishes frequently serve for supporting the inner structure (Fig. 5). All this tends to reduce the internal inductance and inter-electrode capacitance of the tube which are important factors in limiting maximum frequency producible by the tube. A representative of such specially designed u-h-f tubes is the well known type 880 (55). Another type is the 530 tube shown in Fig. 6, designed for special services. It may be noted that this was the first practically used high-voltage water-cooled tube having a heavy thoriated filament.

Instead of inverting or folding up the anode portion to which the glass bulb is attached, some of the newest u-h-f tubes are built with "Kovar" skirts attached to the copper anode by brazing (Fig. 7). Kovar was originally developed by Howard Scott for mercury vapor tubes (56), in which copper cannot be used. Being a magnetic material it was carefully avoided in high-frequency tubes. Recently, however, Kovar seals found application in many high-frequency designs, being advantageous from a manufacturing viewpoint. Indeed, Kovar-to-glass seals do not require fine maching of the metal edge, hence, such seals are easier to make than copper seals; in addition they are mechanically stronger. The basic difference between the Housekeeper and Kovar seals is that thermal expansion of Kovar matches that of certain types of hard glass; that is why there is no necessity for critical machining of the anode end to an extremely thin feather edge, as is the case with copper.

Ultra-high frequency generators from several megacycles to one hundred or more megacycles—in addition to their uses in television and FM—have also found important applications in industry for effective heating of a great variety of dielectric materials. The physical phenomena underlying dielectric heating have been known since alternating current had been produced by Werner Siemens, not quite 100 years ago. But up to 15 years ago the phenomenon was viewed merely as a nuisance. The first attempts to utilize it for practical purposes were made by the Research Laboratories at East Pittsburgh in 1930–1934 in cooperation with Mr. J. H. Davis, chief engineer of the Baltimore and Ohio Railroad. A series of experiments was carried out for desinfestation by high-frequency of grain in bulk, frequently contaminated by rice weevil. Millions of bushels stored in grain elevator sometimes perish from this evil (57). About the same time, in cooperation with the H. J. Heinz Company experiments were also made on sterilizing expensive breakfast foods in packages. From the research viewpoint all these and similar experiments were a real success. An incredible

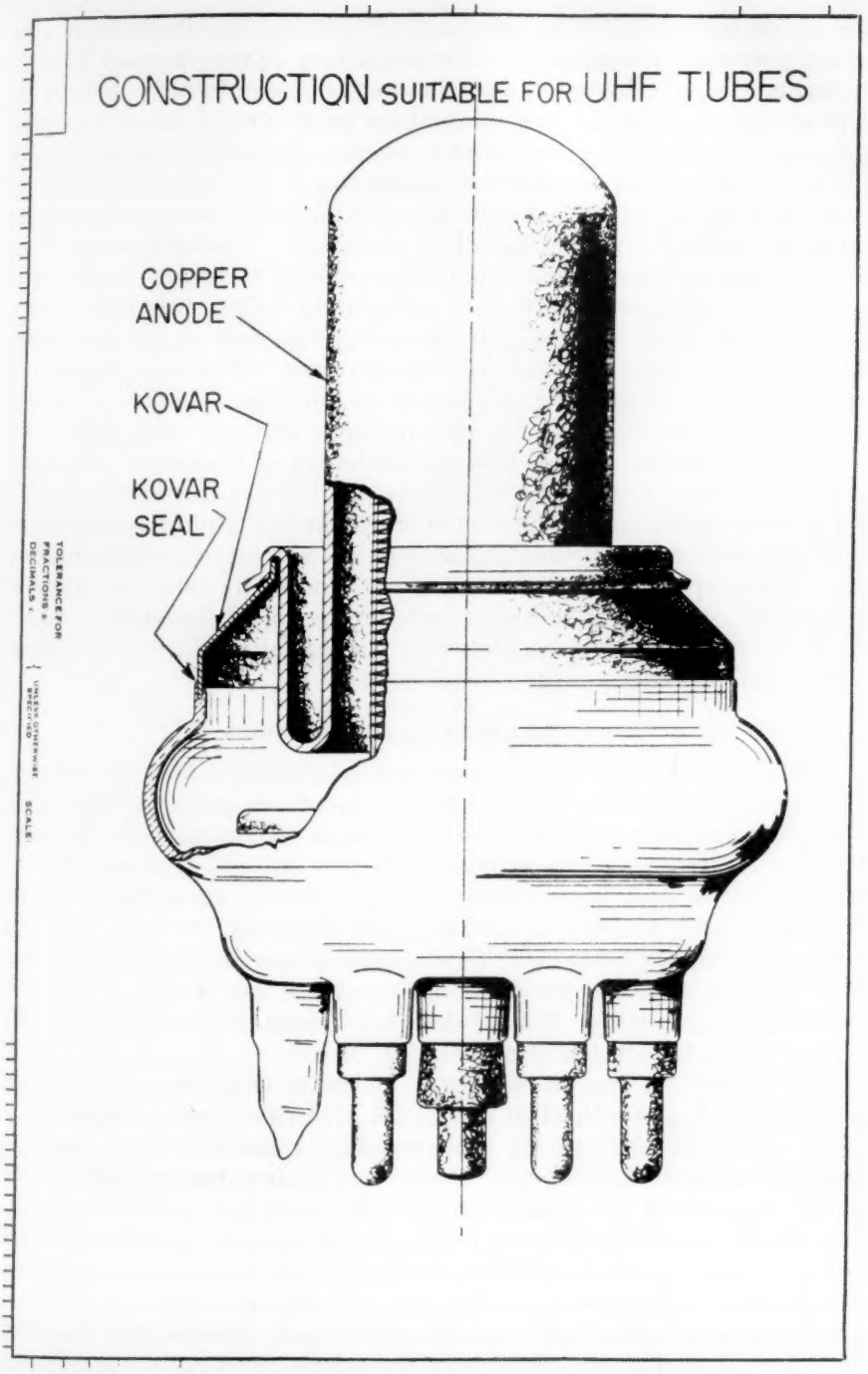

FIG. 7. A copper anode with kovar-to-glass seal, for a large tube.

variety of ultra-high frequency applications to various branches of industry were then suggested. The restaurant owners wanted to cook steaks and chops by high frequency before the eyes of hungry customers; meat packers saw in it a new method for treatment of hams, sausages and other products before storing them; chocolate manufacturers believed to have found an effective means to get rid of swarms of moths before they infest the chocolate mass; glass manufacturers were anxious to use h-f method in preparing safety glass, etc. Enthusiasm for u-h-f heating went so far that some morticians offered to furnish corpses for development of a new method of embalming. But, this enthusiasm was not long lived as, generally speaking, the cost of the necessary equipment proved to be prohibitive at that time. This was augmented by the rapidly progressing depression of the last decade. The war revived many of those embryonic projects and put numerous new demands to industry. High cost was no longer an obstacle. In result, dielectric heating during the recent years was advantageously applied in a variety of industries, such as heating plastics while forming them, preparing parts from plywood in competition with metals, curing rubber, etc. These applications are now widely known as they are subjects of numerous articles in technical and non-technical literature. Many of the new methods will undoubtedly survive after the war as giving better results, sometimes at a lower cost.

SUPER-HIGH FREQUENCY ELECTRON TUBES.

With the existing trend to extend television, FM and ordinary communication into the band of several hundreds and even thousands of megacycles-per-second new electronic tools will be necessary, because triodes or tetrodes of conventional designs fail to give satisfactory performance at such frequencies because of the "electron transit time" limitations and because of discontinuity between the tube and the oscillating circuit. However, new solutions can be found in devices of a different type known for some years but not widely utilized in commercial practice for lack of demand. Such are, for example, the magnetron and the velocity modulation tubes.

The *magnetron* has been known for more than 20 years; it was invented by Dr. A. W. Hull mainly as a rectifier, power inverter, or power control device (58), in other words, for services where mercury vapor tubes are now effectively used. E. Habann first studied a "split plate" magnetron for generation of high-frequency oscillations (59). But, about 1928, Yagi (60) and Okabe (61) discovered that a magnetron with a cylindrical anode split longitudinally into two or more segments was capable of producing oscillations of extremely high frequencies. Enormous work on magnetrons theoretical and experimental has been done since all over the world. Quite recently, a novel type of magnetron which has been developed by two Russian engineers, Alexeiev and

Maliarov (62), was described in the literature. In their tube (Fig. 8) several magnetrons are actually combined in a single body, and instead of the conventional transmission line, cavity resonators are used as oscillating circuits. The authors report 300 watt output in CW operation at frequencies at which one or two watts (63) or even a fraction of a watt were previously considered as an achievement (64).

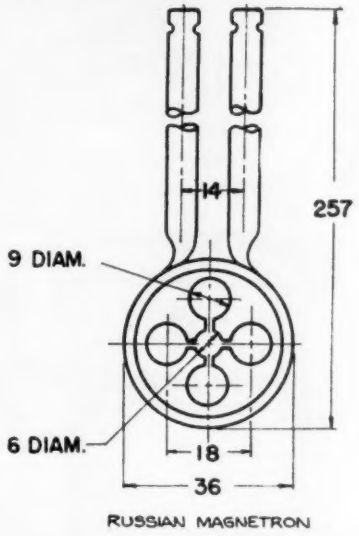

FIG. 8. Multiple water-cooled magnetron of Russian design for very high frequencies.

Another "unusual" type of tube is the Klystron (Fig. 9). This is an *electron beam* and *velocity modulation* or *velocity variation* tube. A number of beam oscillators has been suggested in the past. In fact, as far back as 1908, von Lieben constructed a magnetically controlled beam tube for reception of radio waves (65) even before the grid-controlled tubes made their appearance. The first velocity variation tube was described by the Heils in 1935 (66). However, all early beam oscillators intended for generating very high frequencies were not successful, because there was no adequate oscillating circuit type available to match the extremely high impedance of the electron beam. It was not until Hansen (67) had studied and popularized the "cavity resonators" of Lord Rayleigh (68) that the first practical velocity variation beam tube was constructed by the Varian brothers (69) under the name of *Klystron*. Other contemporary u-h-f beam tubes were described by Haeff (70), by Hahn and Metcalf (71) and by some others.

One of the most recent developments in this field is the single and double-cavity velocity modulation tubes of the "reflex" type, utilizing secondary emission of the target (electron collector). These tubes deliver a considerably greater high-frequency output than similar tubes

not taking advantage of this phenomenon. Dr. Wang undoubtedly will soon publish a paper on this subject.

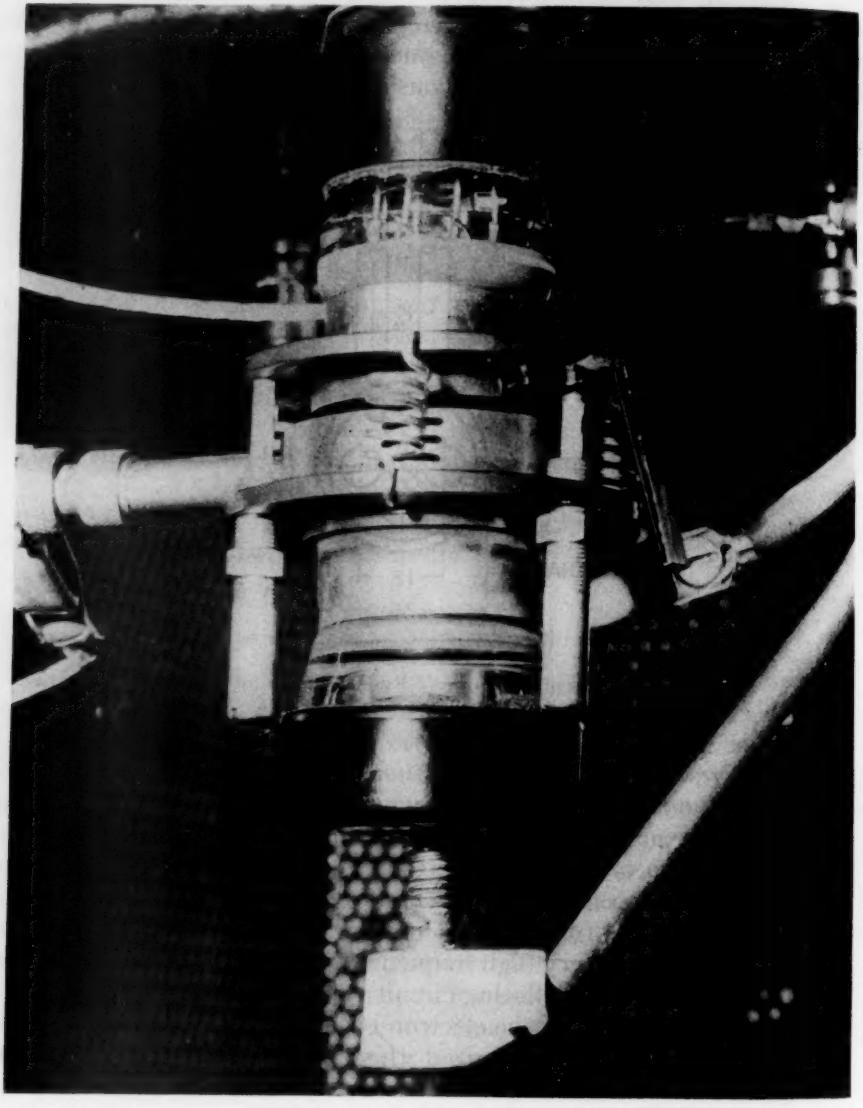

FIG. 9. A single cavity Reflex-Klystron, utilizing secondary emission from target.

The fact that super-high-frequency or micro-wave generators and their circuits are now well developed, will be first reflected in almost a 100-fold increase of frequency band available for communication, FM, television and industry. It is not impossible that special frequencies will be assigned in the future to various professional organizations, such

as doctors, engineers, lawyers, farmers, labor gangs: each may have waves of their own for contacting their business centers, headquarters, or homes while detached from ordinary telephone communication. One may imagine that micro-wave radio communication may enter the field of the private household. In some special industrial processes microwaves may be advantageously used in post-war time as the effect of dielectric heating is proportional to frequency of the electro-magnetic field. Another specific field for super-high-frequency tubes will be their application in therapy as there are indications that they may be of particular effectiveness in treatment of some internal diseases, since they can be focused on any desired internal organ. Indications are also that pulsing super-high frequency energy instead of using continuous oscillations may give still better results.

PHOTOTUBES.

A very important type for modern industry is the inconspicuous phototube. Its pedigree is not connected either with the Crookes discharge tube or with the Edison Effect. The photoelectric effect was first observed by Edmonde Becquerel in 1839 (72); but it was closely studied only after its rediscovery and thorough description by Heinrich Hertz as a result of his famous experiments with electromagnetic waves. Subsequently, photocells of copper oxide type were developed by Hallwachs in 1904 (73) and of alkali metal type by Elster and Geitel in 1912 (74). Now the phototube has become the basis of many industrial control and regulation devices, such as processing, controlling, protection schemes, matching colors, counting, sorting, etc. in a great variety of industries. As its outstanding outgrowth, one must consider the photo-sensitive screens in the modern pick-up tubes without which television could not become practicable.

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THE TRANSIENT PERFORMANCE OF PROPELLERS AND SHIPS DURING BACKING AND REVERSAL.

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PART I.

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1. INTRODUCTION.

The electric propulsion of ships has created a number of problems in the hydrodynamical and in the electrical field the solution of which may lead to a design of propellers and motors giving the shortest possible stopping time and headreach of the vessel after sudden reversal from full speed ahead. Until now the knowledge of the backing forces of propellers has been developed almost entirely experimentally and for the steady state. Tests on the actual ship combined with model tests on ship and propeller, or on the propeller alone, have given us a general knowledge of the performance of thrust and torque during reversal of the propeller and ship. In particular the extensive experiments of S. M. Robinson [1,3] and his successors [7–9,14,16–19] have shown that the characteristics of thrust T and torque Q after backing of the propeller change their signs and develop as in Fig. 1 for constant velocity V of

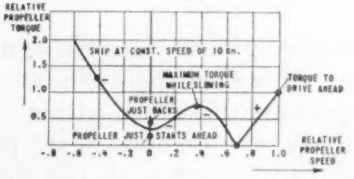

FIG. 1. Propeller torque vs backing propeller speed measured by S. M. Robinson on "U.S.S. Jupiter."

the vessel. The propeller motor must be capable of exceeding the torque maximum between full and zero speed of the propeller and must give a substantial torque after complete reversal of its speed.

[1] See Bibliography, page 226.

This paper analyzes the phenomena during the backing and reversal of a propeller at any velocity of the ship and derives thrust and torque characteristics by the use of well-established hydrodynamical considerations. It attains the objective by subdivision into four steps: first, we consider the actual hydrodynamical flow of the water under varying conditions by means of streamline patterns; second, we derive the forces of reaction of the water column through the propeller; third, we consider separately, although summarily, the effects of the propeller blades on the water column; fourth, we derive the transient inertia effects of the water moved by the propeller. The conclusions of this analysis are in good agreement with the many experimental results; moreover, they give quantitative information with respect to the reversal time and headreach of the ship, dependent on the characteristics of the propeller and its motor.

2. WATER COLUMN THROUGH THE PROPELLER DURING REVERSAL.

The driving forces between water and ship are due to the formation of a jet or column of water by the propelling element. Without production of a jet no continuous thrust can be developed to drive or back the ship. Thus, we start our investigation with a consideration of the production of a simple water column. Figure 2 shows that with the propeller revolving, but stationary in space, water is accelerated by suction from all directions about the propeller, concentrated into a column emerging from the pressure side of the propeller and then streams away unidirectionally in a definite jet. The external boundary of this water column forms a thin vortex layer, which actually is unstable and dissolves into a series of larger vortices, thereby dissipating gradually some or all of the energy of the expelled column. Figure 2 does not emphasize the minor details of the jet formation, such as: contraction of the jet, rotation of the column, vortex formation at the rim of the column, non-uniform distribution of the velocity over the column, and the many other items which make the difference between the actual performance and our idealization which aims to cover the phenomena of primary importance.

The streamlines in Fig. 2 have marked similarity with the water flow in a Borda orifice. However, there are three differences: first, the propeller produces a pressure difference within the orifice and thereby the streamlines actually change direction at the propeller plane; second, centrifugal forces due to a rotation of the water column oppose a convergence; and third, the static pressure along the external boundary of the jet is not constant, but increases from the edge of the jet to infinity on the left in Fig. 2, due to the pressure drop of the inflowing water which here is in contact with the column. These three circumstances change the convergence * of the column as compared with a

* The usual propeller theories derive a contraction factor $k = 1/2$ by combining the theorems of momentum and of energy with the assumption that the energy of the wake is

Borda orifice. The diagram of Fig. 2 is shown for a two-dimensional case because the use of three-dimensional streamlines would lead to unnecessary complications when used for superposition. Thus the following diagrams will show qualitatively, by graphical representation, the phenomena occurring, while the quantitative analysis will be performed by calculation.

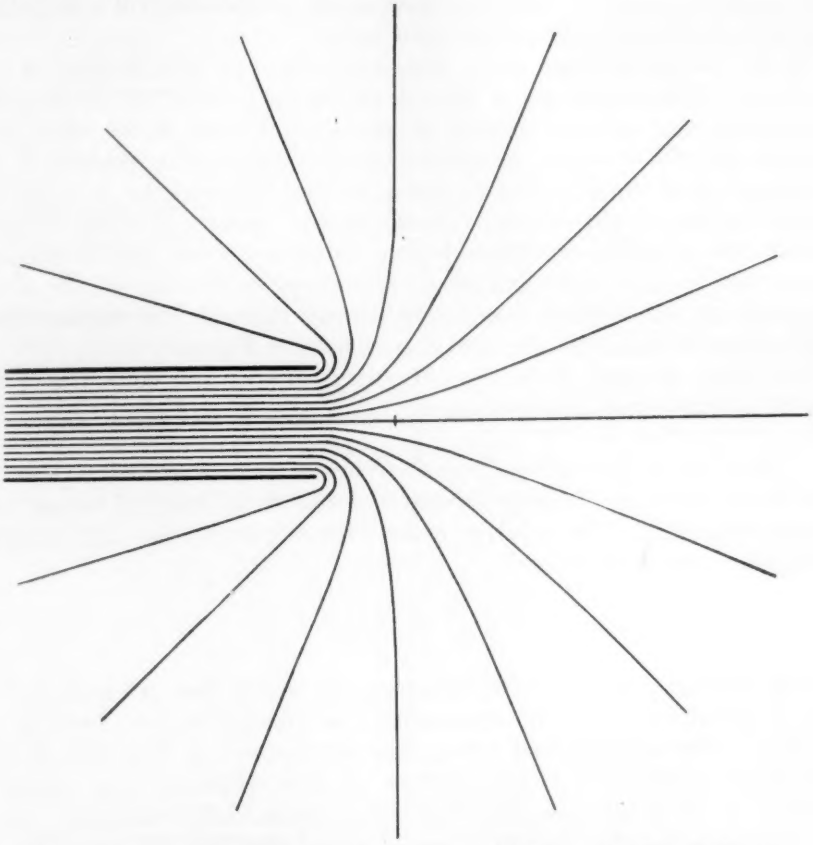

FIG. 2. Streamline pattern formed by concentric inflow and unilateral ejection of water by a stationary propeller.

For the sake of simplicity and in order to emphasize the main phenomena in the analysis of the propeller performance, we omit the interaction between ship and propeller. In particular, we neglect the effects of the absolute axial inflow velocity† and of the convergence and turbulence of the inflowing water, all due to the streamlines around the

completely lost. However, judging from the general experience with rotating water flow in divergent nozzles, it must be concluded that actually a part of the wake energy will be regained from a rotating slip stream, leading to a different coefficient of contraction.

† Appendix 1 analyzes the influence of the forward wake.

hull and the viscosity of the water.[20] Since wake velocity and slip of the propeller column during reversal are much greater than at normal drive ahead, the error caused by these omissions is relatively small. We further neglect the interaction between the propeller and the surface of the water, where by suction and excess pressure before and behind the propeller, waves are produced which travel away and dissipate a part of the propeller power. Thus we consider the performance of a propeller immersed deeply in undisturbed open water.

In the diagrams Figs. 3–10, the streamlines of the water flow of Fig. 2 are superposed on a set of uniform, horizontal streamlines representing the relative motion of the surrounding water when the revolving propeller moves in space along its axis. The velocity V of the surrounding water, equal to the negative ship velocity, is taken as constant in these eight figures. However, the velocity U of the column through the propeller is changed from three times the ship's velocity to zero and further to values up to the negative velocity of the ship. The resultant streamlines are drawn merely through the intersections of this uniform field and the convergent field of Fig. 2.

The wake velocity W, as the difference between the velocities of the propeller column and of the ship, is:

$$W = U - V. \tag{1}$$

This is the absolute velocity in space of the water column behind the moving propeller. The relative wake with respect to the ship velocity or the slip ratio is therefore

$$s = \frac{W}{V} = \frac{U - V}{V}. \tag{2}$$

The various parameters determining the water flow are indicated in Figs. 3–10 which show the streamlines as viewed by an observer on the ship. The undisturbed water flow superposed on Fig. 2 is plotted throughout with $V = 8$ streamlines on the width of the propeller column, so that all diagrams become geometrically uniform. Since Fig. 2 represents the absolute flow of water through the propeller for an observer at rest for whom the water, ejected with a velocity W, emerges towards the left hand, the propeller is driving the ship to the right hand. It is necessary, therefore, to invert this diagram for those figures in which the actual propeller column is expelled towards the ship, namely to the right hand. In this way, Figs. 3–10 show the resultant streamlines about and through the propeller for various column velocities U. The shape of the streamlines always is determined solely by the velocities and the jet formation of the propeller.

Figure 3 is based on a propeller speed $U = 3V$. This means that $3 \times 8 = 24$ streamlines are sucked into the propeller and ejected into the column by action of the propeller. The absolute speed of the wake

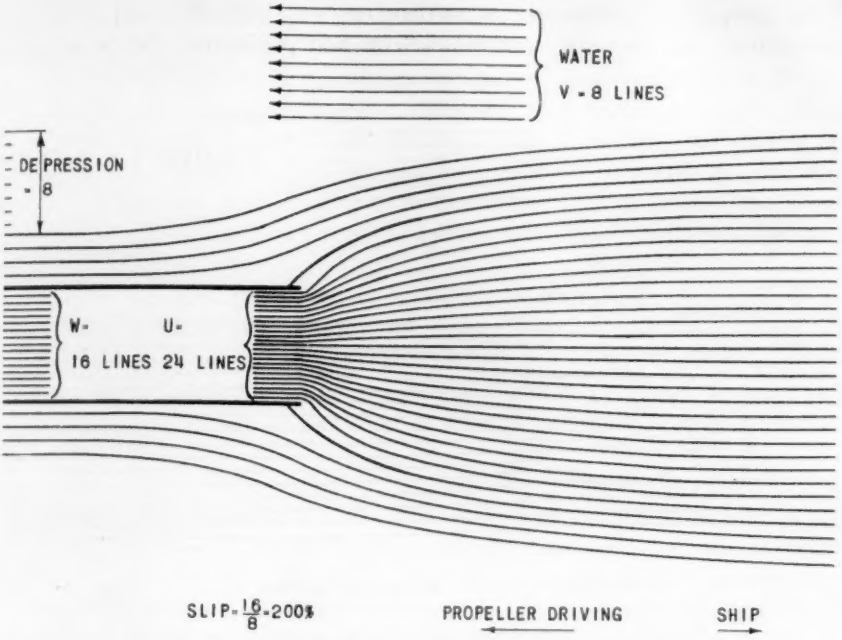

FIG. 3. Streamline pattern formed by a moving propeller ejecting water astern at 3 times the ship's velocity.

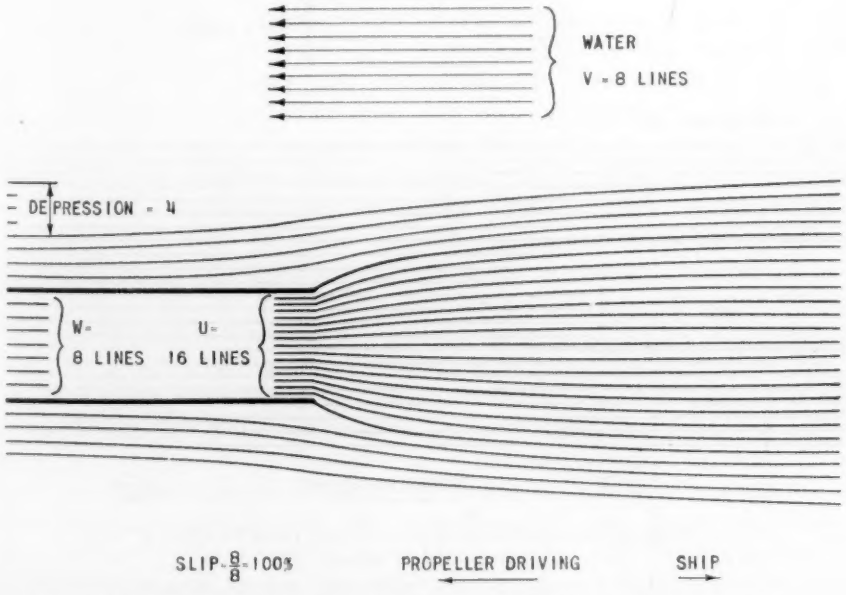

FIG. 4. Streamline pattern formed by a moving propeller ejecting water astern at 2 times the ship's velocity.

of the propeller column is, according to eq. (1), $W = 24 - 8 = 16$ streamlines, and the slip is $s = 16/8$ or 200 per cent. Such relations

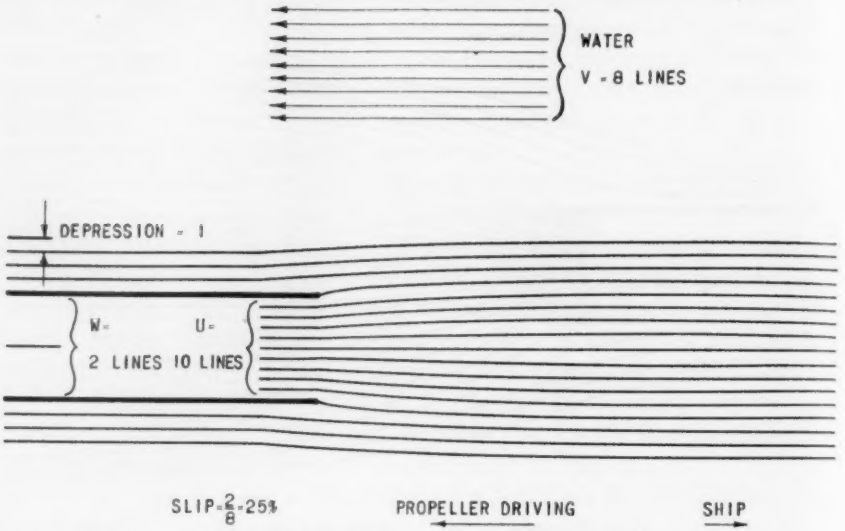

FIG. 5. Streamline pattern formed by a moving propeller ejecting water astern at 1.25 times the ship's velocity.

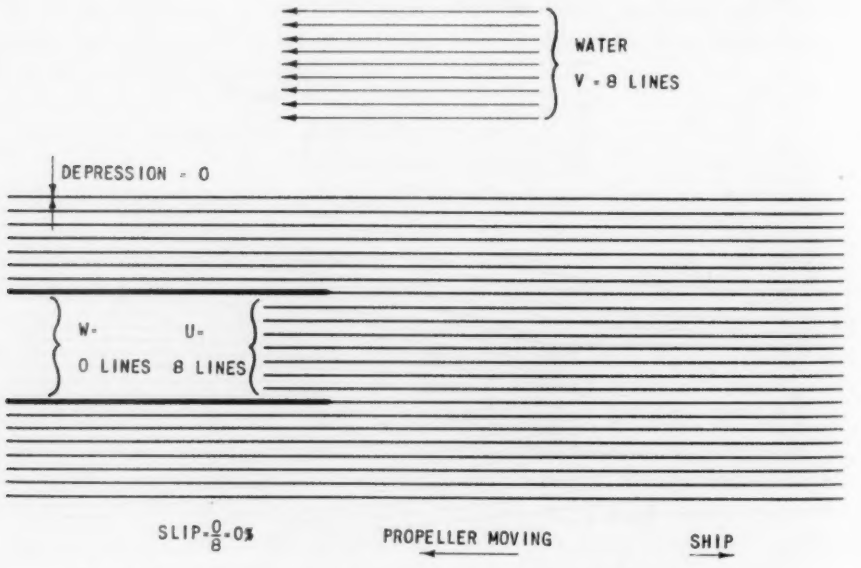

FIG. 6. Streamline pattern formed by a moving propeller ejecting water astern at ship's velocity.

are present in tugboats which are working with high thrust at small speed. The diagram shows the heavy acceleration of the propeller

water before entering the propeller disk, causing a depression of 8 streamlines in this two-dimensional picture.

Figure 4 shows the streamlines forming a water velocity of $U = 2V = 16$ streamlines in the propeller column. The wake therefore contains $W = 16 - 8 = 8$ streamlines, giving a slip s of 100 per cent., with much smaller suction and depression. The depression of the water surface, however, both here and in the other figures is no quantitative indication for the actual pressure before or behind the propeller in the three-dimensional case.

In Fig. 5 the propeller drives the water with $U = 5/4V = 10$ streamlines, producing a wake of only $W = 10 - 8 = 2$ streamlines and a slip s of 25 per cent. Such shape of the streamlines is present in most seagoing vessels during ordinary travel, the slip usually being of the order of 15 to 30 per cent. The depression here is reduced to only 1 streamline.

In Fig. 6 the water velocity through the propeller is taken equal in magnitude and opposite in direction to the velocity of the ship so that the propeller screws itself synchronously through the water with a velocity $U = V = 8$. Therefore this diagram shows no disturbance of the streamlines, which flow undistorted through the propeller, and therefore no interaction occurs between propeller and water. Here the surface of the propeller column has no significance.

In Fig. 7 the water through the propeller has one-half the ship's velocity so that the propeller is resisting the movement of the ship. Thus the propeller acts as a water-motor taking energy from the water stream. With velocity of $U = 4$ streamlines in the column behind the propeller the water now moves slower than the ship, giving an absolute wake velocity of $W = 4 - 8 = -4$ lines and a slip $s = -2/4$ or -50 per cent. The streamlines now show a certain elevation instead of a depression, a consequence of the propeller backing the ship.

In Fig. 8 the streamlines are shown with the propeller water at rest, $U = 0$, as seen from the ship, while the ship is moving with full velocity V ahead. If a quiescent propeller actually prevented the flow of water through its disk, the streamline diagram of Fig. 2 would cease to exist. A simple superposition of a non-penetrable propeller disk and a uniform flow of water would give a diagram in which, in contrast to Fig. 8, the streamlines would close themselves behind the propeller disk. However, by action of vortex and jet formation, the actual streamline diagram is more nearly that of Fig. 8 because a water velocity $U = 0$ in the propeller disk deflects the incoming streamlines around the rim but leaves a wake behind the propeller disk the shape of which in Fig. 8 is merely an idealization. Thus, in this case the formation of a column is not due to the propeller action proper but to vortex action behind the quiescent propeller disk.

Figure 9 shows the streamlines for reversed propeller rotation so

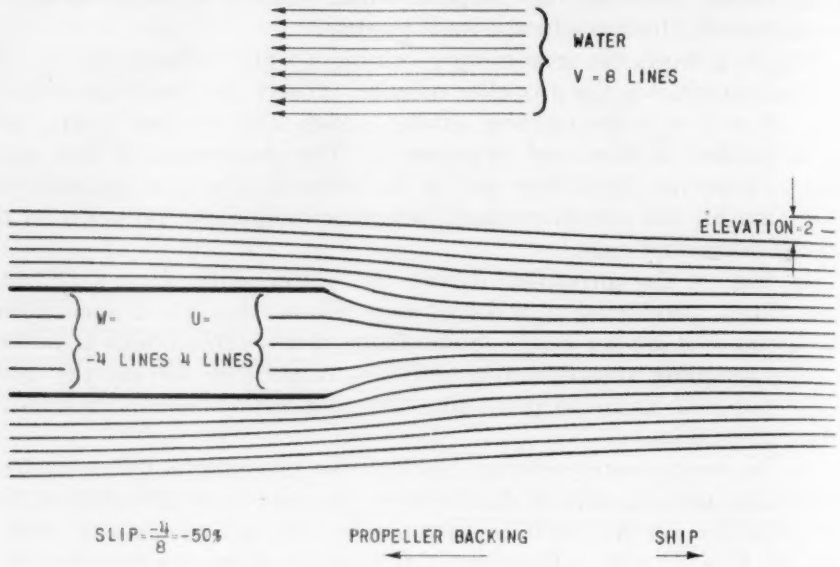

FIG. 7. Streamline pattern formed by a moving propeller ejecting water astern at ½ the ship's velocity.

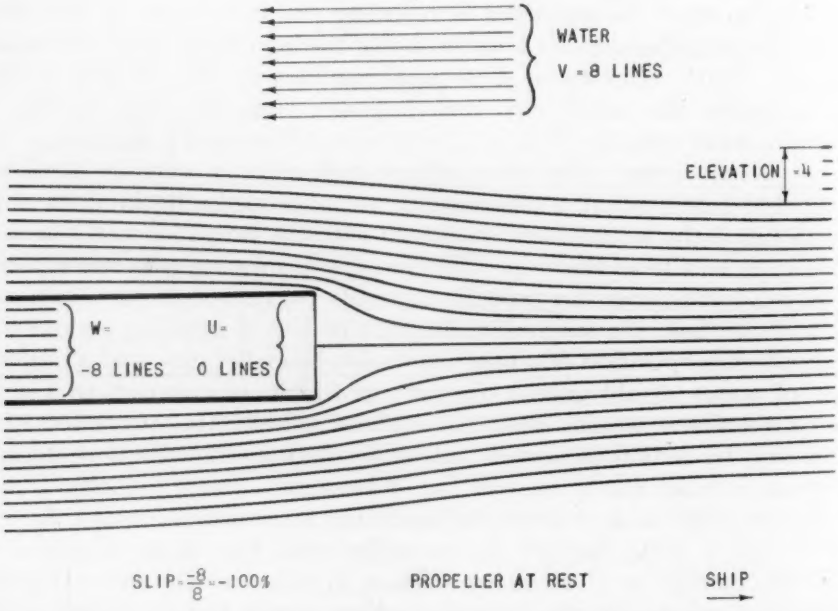

FIG. 8. Streamline pattern formed by a moving propeller rotationally standing still.

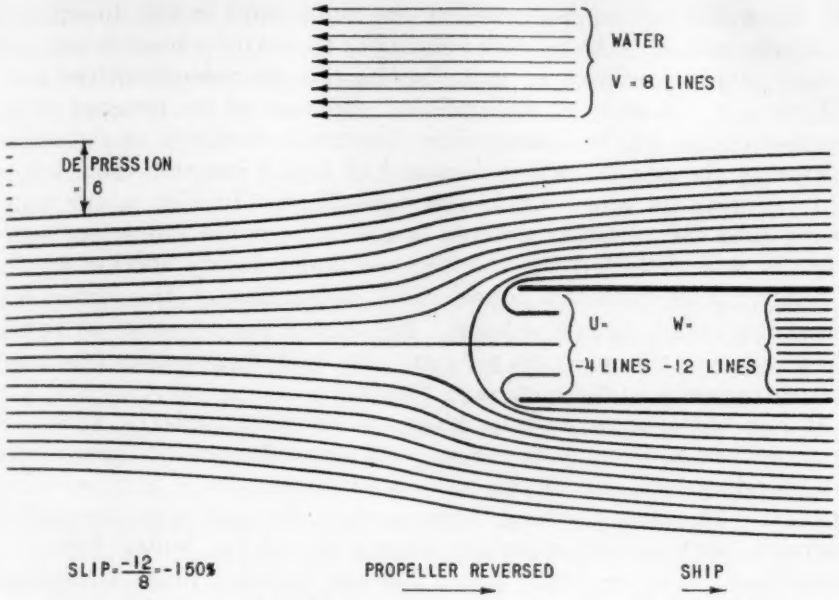

FIG. 9. Streamline pattern formed by a moving propeller ejecting water ahead at ½ the ship's velocity.

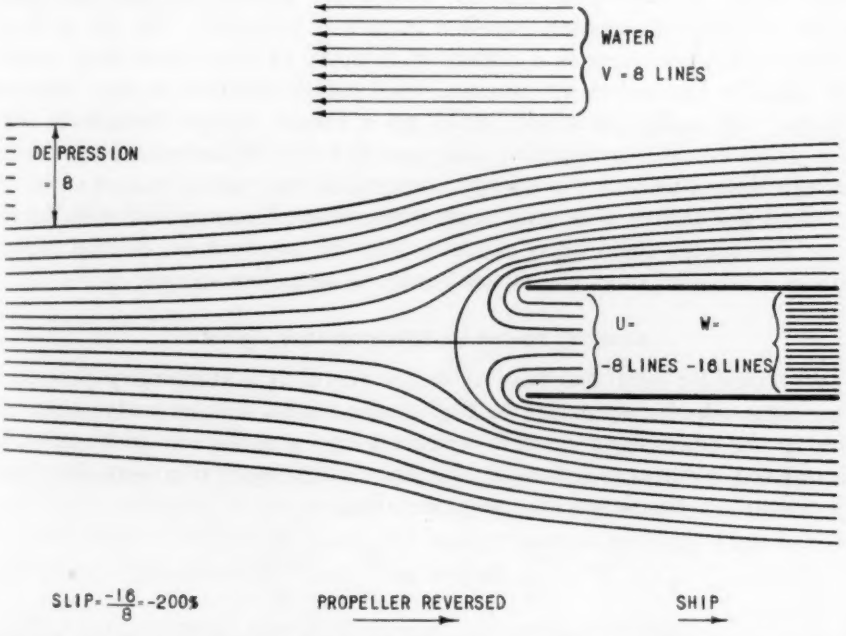

FIG. 10. Streamline pattern formed by a moving propeller ejecting water ahead at ship's velocity.

that the water column is ejected to the right hand in the direction of the ship's motion. The relative velocity of the water column is assumed as $U = -4$ streamlines, so that the absolute jet velocity of the wake is $W = -4 - 8 = -12$ streamlines. Because of the reversal of the direction of the jet, this streamline diagram is designed as the superposition of the parallel water flow and of Fig. 2 inverted from left to right, ejecting its water jet to the right hand. In Fig. 9, the water flowing into the propeller column is taken from the oncoming water which is now deflected by 180 degrees under heavy suction by the propeller. This causes a considerable depression of the water flow behind the vessel, namely 6 lines. The slip of the propeller jet in this case is $s = -12/8$ or -150 per cent., the backing propeller producing a thrust opposite to the motion of the ship.

In Fig. 10 the propeller is backing with full water velocity, $U = -8$, giving a wake of $W = -8 - 8 = -16$ streamlines which flow ahead, corresponding to a slip of the propeller column $s = -16/8$ or -200 per cent. Therefore a strong thrust against the motion of the vessel is produced, with a corresponding depression of the water flow of 8 streamlines. The reversed water column includes more streamlines than before and therefore the depression behind the propeller is greater.

As a whole, we see from these streamline diagrams, Figs. 3–10, that throughout the entire period of reversal of the propeller from full speed ahead to full speed astern, the water moved by the propeller can be considered as being expelled in jets or columns. At the surface of these columns there is a different velocity of the water flow inside and outside the column, causing substantial friction at the column surface. In reality this will build up a larger vortex formation and these ring vortices gradually will equalize the differences in velocity through dissipation of the energy content of the ejected water column. We shall not follow this later transformation of energy but will determine the forces correlated to the original production of the water column, extended over the entire range of propeller speeds.

3. REACTIVE FORCES OF THE PROPELLER COLUMN.

We consider first the flow of water through a stationary propeller plane near which, according to Fig. 2, the radial flow of water from all sides to the propeller region is deflected into a unilateral movement in the ejected column. According to the principle of momentum,[15] this will produce a thrust on the propeller disk

$$T = \frac{d}{dt}(mv) = m\frac{dv}{dt} + v\frac{dm}{dt}, \qquad (3)$$

v being the velocity of the water, m the mass transported, and t the time. The second term on the right-hand side refers to steady-state

movement of the water where the velocity is constant with time, while the first term stands for an additional force under transient conditions.

The water obviously is accelerated to an axial velocity in the propeller plane given by the wake velocity W. If, however, the water jet suffers a contraction behind the propeller plane, giving a higher velocity, then the maximum velocity up to which the water is accelerated becomes

$$v = \frac{W}{k}, \tag{4}$$

k being a coefficient of contraction. The energy corresponding to this velocity v of the column is usually considered as lost and as dissipated by vortex formation. The coefficient of contraction for a Borda jet is $1/2$, a value often assumed in the theory of propulsion. However, it is probable that the actual coefficient is much nearer 1, for the reasons given in Section 2. We will not assume a definite value of this coefficient in our equations, but obtain the advantage even to consider k as slightly changing over the various ranges of operation.[11,12]

If W is the absolute axial water velocity through the propeller plane, eq. (4) remains valid whether the entire flow of Fig. 2 is standing in space or moves with any velocity V along its axis, k always denoting the coefficient of contraction of the equivalent standing jet.*

The flow of water through the propeller disk of area A transports a mass per second

$$\frac{dm}{dt} = \rho A U, \tag{5}$$

U being the relative water velocity through the propeller area and $\rho = \gamma/g$ the specific mass of the water, given by density over gravity.

For steady-state movement the velocity v remains constant and therefore the first term on the right-hand side of eq. (3) vanishes. The thrust produced by formation of a water column, moving as a whole with a velocity as in eq. (4), is therefore

$$T = \frac{\rho}{k} A U W = \frac{\rho}{k} A U(U - V). \tag{6}$$

On the right-hand side the wake velocity W has been expressed by the velocity V of the ship, using eq. (1). This fundamental eq. (6) is the same as used in all propeller theories, except that ordinarily the contraction coefficient is taken as $k = 1/2$, which appears to be too low.

The power impressed upon the water column moving with velocity U through the propeller is

$$P = TU = \frac{\rho}{k} A U^2 W = \frac{\rho}{k} A U^2(U - V), \tag{7}$$

* Appendix 2 analyzes the contraction of the moving jet.

and the efficiency of propulsion for drive ahead with respect to the water motion alone is

$$\eta = \frac{TV}{TU} = \frac{V}{V+W} = \frac{1}{1+W/V} = \frac{1}{1+s} \tag{8}$$

if we use eqs. (1) and (2).

Since the area A of the propeller disk, the mass density ρ of the water, and the contraction coefficient k are given values, we may divide eq. (6) by these parameters and obtain the relative or specific thrust as

$$\bar{T} = \frac{T}{\frac{\rho}{k}A} = UW = U(U-V). \tag{9}$$

This characteristic value is to be measured in units of velocity squared.

Since the specific thrust on the propeller is dependent only on the column velocity U of the water through the propeller and the travelling velocity V of the propeller and ship, we can represent it by a set of curves as in Fig. 11, dependent on U for various constant values of V.

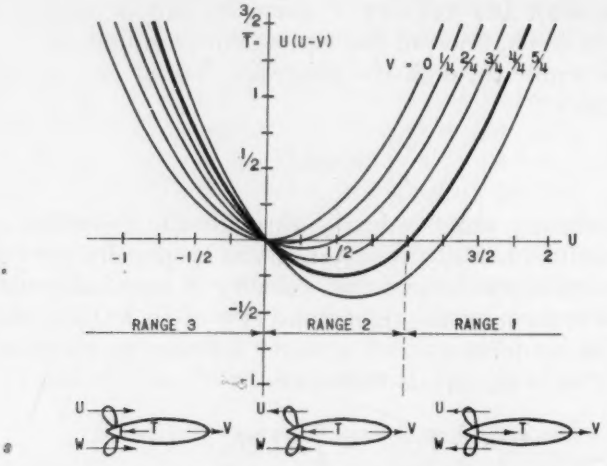

FIG. 11. Analytical propeller-thrust vs velocity of water column for various ship velocities.

The propeller characteristic therefore is a parabola passing through zero at two points, $U = 0$ and $U = V$, meaning, on the one hand, standstill of the propeller water and, on the other hand, synchronism between propeller speed and ship velocity. For steady-state travel of the ship in range 1, U is greater than V, the propeller column is ejected astern, and drives the ship. If the ship velocity V is constant, as in the heavy curve of Fig. 11, and the propeller gradually decreased in speed, then at synchronism of propeller and ship the thrust passes

through zero and becomes negative if the column velocity U becomes smaller than that of the ship V. This continues during the whole range until U becomes zero. In this range 2, therefore, the propeller is driven by the ship and acts as a water-motor, retarding the ship's movement. While for $U > V$ the propeller drives the ship, for $U < V$ the ship drives the propeller and the propeller takes energy from the water. The propeller machinery must be able to dissipate this energy. The streamlines of this state are shown in Fig. 7.

If the water velocity U in the propeller column becomes negative, enforced by reversal of the revolving propeller, the thrust according to eq. (6) or (9) again appears positive, meaning that the propeller delivers energy to the water. This thrust, however, does not drive the ship ahead since Figs. 9 and 10 show that the water column now is ejected in the direction of travel. Thus, in the range 3 also, the thrust retards the ship, as it did in the range 2 of Fig. 11.

Equations (6) and (9) are rigorous analytical expressions for the magnitude of the thrust; however, the direction of the thrust is not determined by them. The thrust with every jet formation always is directed opposite to the absolute jet velocity in space, which is expressed by the wake velocity W in eqs. (1) and (4). Thus the direction of the thrust T in eqs. (6) and (9) is determined by the direction of W and not of U, as indicated at the bottom of Fig. 11. Therefore, with respect to the heavy curve in Fig. 11, we see that in range 1, comprising the ordinary drive of the ship ahead, wake and thrust are positive; in range 2, with backing propeller, both are negative; and in range 3, with reversed propeller, wake and thrust are also negative from the viewpoint of the ship. Hence, if we wish to plot the direction of the thrust consistently with respect to the movement of the ship, we must bring the branch of the T-curve in range 3 down to the negative side of the diagram and obtain in Fig. 12 a curve of thrust versus propeller speed or, better said, water column velocity, which gives correctly both magnitude and direction in space.

In making this change of sign, note that the ordinary law of water resistance, being proportional to the square of the velocity, also gives only the magnitude of the resistance but not the direction of the force when changing from positive to negative velocity. The parabola in Fig. 11 for $V = 0$ corresponds to this well-known case. Thus we see that there is no contradiction in determining the direction of the thrust independent of its analytical formulation.

If in contrast to Fig. 11 we maintain constant the water velocity U through the propeller but vary the ship velocity V, then the straight lines in Fig. 13 represent eq. (9) and show the variation of the thrust with changing V for a number of propeller speeds or column velocities U. For example, if the water column has been completely reversed by the propeller so that U is negative and the ship is backed, as shown by

the heavy line of Fig. 13, the retarding thrust decreases linearly with decreasing velocity of the ship. When the ship has been brought to rest, there is still a strong backward thrust which drives the ship gradually astern, until this decreasing thrust is balanced by the increase

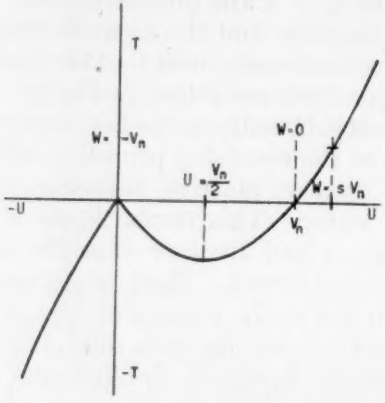

FIG. 12. Actual propeller thrust vs velocity of water column through propeller.

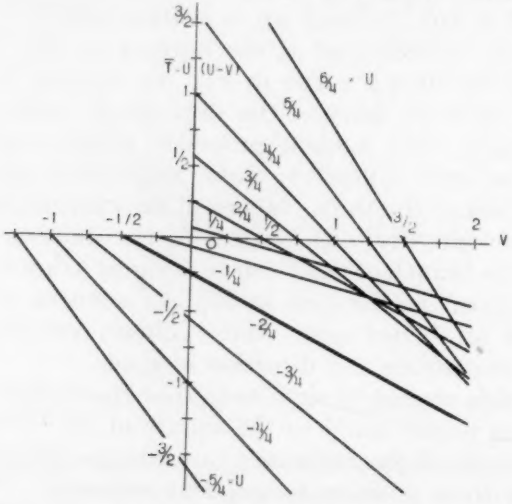

FIG. 13. Actual propeller thrust vs ship velocity for various velocities of water column.

in the water resistance of the ship. In order to comply with the direction of the thrust, just considered, the thrust lines in Fig. 13 are also changed to the negative side where necessary, depending on the actual direction of the wake *W*.

The thrust curve of Fig. 12 resembles closely the characteristics of screw propellers during reversal as measured by many investigators,[1-19]

and shown in Fig. 1. They all have found for the propeller torque and thrust: an inversion of sign when the propeller speed is reduced below synchronism with the travel of the ship; a negative maximum at about one-half the ship velocity; a deep depression at propeller speed zero; and a sharp increase of the negative values for reversal of the revolving propeller. We have derived the same characteristic here as function of the velocity of the water column rather than of propeller speed, but actually both are closely related and are nearly proportional to each other.

It may be that the contraction coefficient k is not absolutely constant over the driving, backing and reversal ranges of the propeller, due to a change in shape of the water jet behind the propeller disk. Then the actual thrust, following from eq. (6) or (9), would show a slightly distorted curve compared with Fig. 12, keeping, however, the general character of a broken parabola.

At water velocity zero in the column, the thrust according to eq. (6) or (9) should be zero. However, as Fig. 8 shows and as is described in section 2, in this case the water column is not formed by the propeller rotation but by the ordinary wake behind an impenetrable propeller disk. This is a different phenomenon, not described by eqs. (5) to (9), and therefore it gives an effect additional to the curve of Fig. 12 at $U = 0$. It is well known that a disk having the area a of the propeller blades in a water stream of velocity V by action of the dead water column behind the disk suffers a resistance or drag

$$T_0 = c\rho a \frac{V^2}{2}, \tag{10}$$

giving a specific thrust, corresponding to eq. (9),

$$\bar{T}_0 = \frac{T_0}{\frac{\rho}{k} A} = \frac{kc}{2} \frac{a}{A} V^2 \tag{11}$$

which is represented at $U = 0$ in Fig. 14.

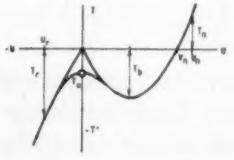

FIG. 14. Additional thrust on moving propeller at rotational standstill caused by drag on propeller blades.

Hence instead of thrust zero, there develops near standstill of the propeller a resistance thrust T_0 which rounds off the break in the thrust curve at $U = 0$ and the adjacent zone, as indicated in Fig. 14. The

relative magnitude of T_0 is determined, in addition to the contraction and resistance coefficients in eq. (11), by the relative area a/A of the propeller blades, and therefore the dip in the thrust curve for $U = 0$ may have a different magnitude for the various propellers actually in use.

With a contraction coefficient $k = 1/2$ to 1, a drag coefficient $c = 1/2$ to $3/2$, and a blade area within the propeller disk of $a/A = 1/5$ to 1, this resistance thrust varies between the limits

$$\bar{T}_0 = \frac{(0.5\text{–}1)(0.5\text{–}1.5)}{2}(0.2\text{–}1)V^2 = (0.025\text{–}0.75)V^2. \tag{12}$$

This may be an insignificant or a considerable amount, depending entirely upon the blade shape of the propeller.

In order to compare this value numerically with the magnitude of the thrust of the backing propeller, we express the specific thrust of eq. (9), substituting the slip s from eq. (2) for the velocity U of the propeller water, by

$$\bar{T} = sVU = s(1 + s)V^2. \tag{13}$$

Therefore at normal speed of the ship of velocity V_n, when the propeller is working with normal slip s_n, the normal specific thrust is

$$\bar{T}_n = s_n(1 + s_n)V_n^2. \tag{14}$$

This gives for various normal slips between the limits of 5 and 50 per cent. the full-speed specific thrusts of the second line of Table 1, expressed in terms of full speed itself. Thus the specific driving thrust depends only on the ship's velocity and on the normal slip of the propeller.

The maximum backing thrust, however, according to Fig. 11 and eq. (9), is independent of the normal slip, and occurs when the retarding propeller gives the water column just a velocity U equal to $1/2$ the ship velocity V. Therefore the maximum backing thrust with slip $s = -50$ per cent. is at constant normal speed V_n of the vessel

$$\bar{T}_b = \frac{V_n}{2}\left(\frac{V_n}{2} - V_n\right) = -1/4V_n^2, \tag{15}$$

which in general is more than the resistance thrust according to eq. (12). The ratio of this maximum backing thrust to the driving thrust at full speed, eq. (14), is shown in the third line of Table 1.

A reversing propeller, for example, with a water column velocity of $U_r = -V_n/2$, produces a much higher thrust which is at constant speed of the ship ahead

$$\bar{T}_r = -\frac{V_n}{2}\left(-\frac{V_n}{2} - V_n\right) = 3/4V_n^2 \tag{16}$$

and increases rapidly with greater propeller speed astern. The fourth line of Table 1 shows the ratio of the reversal thrust of eq. (16) to the

TABLE 1.

Normal Thrust, Backing Thrust and Reversal Thrust, as determined by the Slip of the Wake at Full Speed Ahead.

Normal Slip s_n while driving ahead	5	10	15	20	25	30	35	40	45	50	%
Normal Thrust T_n while driving ahead	0.05	0.11	0.17	0.24	0.31	0.39	0.47	0.56	0.65	0.75	$\times V_n^2$
Backing Thrust T_b/T_n at maximum, as ratio to normal driving thrust	4.75	2.27	1.45	1.04	0.80	0.64	0.53	0.45	0.38	0.33	$\times -1$
Reversal Thrust T_r/T_n at half speed, as ratio to normal driving thrust	14.3	6.82	4.35	3.13	2.40	1.92	1.58	1.34	1.15	1.0	$\times -1$

driving thrust at full speed ahead. Thus for the usual propellers with normal slips from 10 to 30 per cent., such reversal will effect a heavy overloading of the propeller machinery. In general the reversal column velocity has to be restricted to smaller values than $V_n/2$. For tugboats with large normal slip, however, the reversal thrust is moderate and high water column velocities may easily be reached.

If we compare by line 3 in Table 1 the maximum backing thrust of eq. (15) with the propeller thrust at normal speed ahead, eq. (14), we see that with highly efficient propellers having a normal slip as small as 5 to 15 per cent., the maximum backing thrust exceeds greatly the normal driving thrust. For a normal slip of about 20 per cent., which is a good average value for ordinary vessels, the maximum backing thrust is of the same magnitude as the normal driving thrust, and for higher normal slips the backing thrust will always be considerably smaller than the driving thrust. This comparison shows clearly that with propellers of small slip, there must be provided a propeller machinery capable of producing very high backing torque, while with high slip propellers the conditions are much easier. Since the normal slip depends largely on the area of the blades, propellers with large blade area need powerful reversing machinery; on the other hand, they will produce a high backing thrust and therefore will stop the ship in a short time. Since the backing thrust always produces a generating torque, driving the propeller machinery, an additional ordinary friction brake would enable even a weak reversing machinery to overcome the maximum thrust.

The inertia of the rotating propeller and its driving machinery is always very much smaller than the inertia of the traveling ship and

therefore the propeller can be reversed in a period of time during which the ship still retains a high velocity. In Fig. 15 is shown in which manner the propeller thrust develops if the propeller inertia is so small that the ship velocity does not change materially during the reversal of the propeller. Then during retardation of the water column of velocity U, the thrust would first decrease from full value T_n at normal ship velocity V_n to zero at synchronism of propeller and ship, then pass through the maximum backing thrust T_b at half column velocity, decrease again to the minimum thrust T_0 at standstill of the column, and with reversed speed of the propeller attain the high reversal thrust T_r at water column velocity U_r, both determined by the equilibrium between this reversal thrust curve and the thrust-speed characteristic of the propeller machinery.

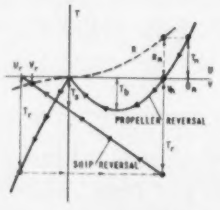

FIG. 15. Development of propeller thrust during propeller reversal and during ship reversal.

After complete reversal of the propeller the ship may still have nearly its original velocity V_n at which now the retarding thrust T_r is produced with the propeller running reversed. Thereby the velocity V of the vessel becomes decelerated by the additional effects of the backing thrust and the ship resistance in the water. While this resistance R with diminishing V decreases from full value $R_n = T_n$ on the dashed parabola in Fig. 15, the backing propeller thrust decreases from T_r on a straight line ending at U_r according to eq. (9) and Fig. 13.

When the ship has come to standstill with $V = 0$, the propeller still exerts a considerable backing thrust

$$\bar{T}_s = U_r^2. \tag{17}$$

This would reverse the ship's velocity gradually, backward to the intersection of the linear thrust characteristic and the dashed resistance parabola for the ship moving astern. Thus finally the ship would travel astern with velocity V_r as indicated in Fig. 15.

4. STOPPING AND REVERSAL PERIODS AND HEADREACH.

After the propeller has reversed the water column, the two forces decelerating the ship can be expressed analytically. For lower than full speed the ship resistance is nearly proportional to the square of

the velocity

$$R = \left(\frac{V}{V_n}\right)^2 T_n, \tag{18}$$

as indicated in Fig. 16. If we substitute here the value of the normal thrust as in eq. (14), the specific resistance of the ship, dependent on the ship velocity V, can be expressed by

$$\bar{R} = \frac{R}{\frac{\rho}{k} A} = s_n(1 + s_n) V^2. \tag{19}$$

The specific thrust of the propeller column, decreasing linearly with the ship velocity V, as shown by Fig. 16 and eq. (9), starts with the

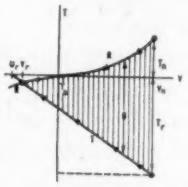

FIG. 16. Joint action of backing thrust and ship resistance at retardation of the ship.

large value T_r corresponding to the full speed of the ship ahead, and decreases to zero at a negative velocity $V = U_r$. The total backing forces on the vessel therefore are determined by

$$\bar{B} = \bar{T} + \bar{R} = U_r^2 + U_r V + s_n(1 + s_n) V^2. \tag{20}$$

This expression already takes account of the negative sign of U_r in reversing state, making the signs of all three terms positive.

The moving inertia mass of the ship is given by the displacement D and the specific mass ρ of the water as

$$M = \rho D. \tag{21}$$

This value may include the virtual inertia mass of the water displaced by the motion of the vessel and increasing the inertia of the ship by 5 to 10 per cent. The retardation of the ship is governed by the law of deceleration

$$M \frac{dV}{dt} = -B \tag{22}$$

and therefore the time of retardation, by use of eqs. (21) and (20), and

substituting the specific backing force, is given as

$$t = -M\int\frac{dV}{B} = -\frac{\rho D}{\frac{\rho}{k}A}\int_{V_n}^{0}\frac{dV}{\bar{B}}$$

$$= \frac{kD}{A}\int_{0}^{V_n}\frac{dV}{U_r^2 + U_rV + s_n(1+s_n)V^2}. \quad (23)$$

This time depends merely on displacement, propeller area and a velocity integral. If we determine the period necessary for retarding the ship to standstill, the limits of the integral are full speed V_n ahead and zero speed.

The integral in this expression is well known and determined by an inverse trigonometric or hyperbolic tangent depending on the value of the discriminant

$$\Delta = U_r^2[s_n(1+s_n) - \tfrac{1}{4}] \gtrless 0. \quad (24)$$

The solution is for $\Delta > 0$

$$\int_0^{V_n}\frac{dV}{\bar{B}} = \frac{1}{\sqrt{\Delta}}\left[\tan^{-1}\left(\frac{U_r/2 + s_n(1+s_n)V}{\sqrt{\Delta}}\right)\right]_0^{V_n}, \quad (25a)$$

but for $\Delta < 0$

$$\int_0^{V_n}\frac{dV}{\bar{B}} = -\frac{1}{\sqrt{-\Delta}}\left[\tanh^{-1}\left(\frac{U_r/2 + s_n(1+s_n)V}{\sqrt{-\Delta}}\right)\right]_0^{V_n}. \quad (25b)$$

However for the value zero of the discriminant corresponding to $s_n = 20.7$ per cent., the integral simplifies to

$$\int_0^{V_n}\frac{dV}{U_r^2 + U_rV + V^2/4} = \left[\frac{-2}{U_r + V/2}\right]_0^{V_n} = \frac{V_n}{U_r(U_r + V_n/2)}, \quad (26)$$

so that in this case the entire stopping time of the vessel from full speed to zero speed is

$$t = \frac{kDV_n}{AU_r(U_r + V_n/2)} = \frac{kD}{AV_n}\frac{V_n^2/U_r^2}{1 + V_n/2U_r}. \quad (27)$$

This result shows that the retardation period is proportional to the displacement D and to the coefficient of contraction k, and inversely proportional to the propeller area A and to the normal speed V_n ahead, and, in addition, the higher relatively the reversal speed to which the propeller can be brought, the smaller is, in nearly quadratic relation, the time for standstill. The latter influence is caused by the large increase of the reversal thrust T_r as shown on the left-hand side of Fig. 15.

We will use in all our numerical computations the metric or m.k.s. system. If we consider, as an example, a vessel of a displacement

$D = 10{,}000m^3$, a single propeller with diameter of $5m$, giving an area $A = 19.6m^2$, driving the ship ahead with $V_n = 20$ knots $= 10.3m/s$ at a slip $s_n = 20.7$ per cent., and a reverse speed of the propeller column $U_r = V_n/2$, then the stopping time becomes, with a contraction coefficient $k = 0.8$ as an average,

$$t = \frac{0.8 \cdot 10{,}000}{19.6 \cdot 10.3} \frac{2^2}{1 + 2/2} = 79 \text{ sec.}$$

which is about 1.3 minutes. This is the smallest possible time for stopping such a ship, and is attainable only under ideal conditions.

For slips s_n other than 20 per cent., a discussion of eq. (23) together with the solution (25a) or (25b) shows that besides the normal slip itself and the ratio U_r/V_n only the characteristic quotient of eq. (27), namely kD/AV_n, decides the value of the stopping time.

It may be noticed that fast vessels have a shorter stopping time than slow ones, since V_n is in the denominator. This is due to the fact that their resistance R and therefore also the propeller thrust T are proportional to V_n^2. Thus the larger backing propeller thrust also retards the ship more rapidly.

We can determine a time constant τ_v of the ship, defined as the time in which a constant thrust of normal value would accelerate or decelerate the ship between standstill and normal velocity. Such a time constant is given by the quotient of normal velocity V_n and normal thrust T_n, multiplied by the inertia mass M of the ship. By substituting for M eq. (21) and for T_n eqs. (9) and (14), we find

$$\tau_v = \frac{V_n}{T_n} M = \frac{V_n}{s_n(1 + s_n) V_n^2 \frac{\rho}{k} A} \rho D = \frac{k}{s_n(1 + s_n)} \frac{D}{A V_n}$$

and with the figures of the example,

$$\tau_v = \frac{0.8}{0.25} \frac{10{,}000}{19.6 \cdot 10.3} = 158 \text{ sec.} = 2.64 \text{ min.}$$

This time constant, however, would express only a quality of the ship proper, not including the propeller and its machinery, and therefore it has a limited significance.

After standstill the ship will accelerate astern under the rest thrust T_s, Fig. 16, until the thrust curve T intersects the resistance curve R of the ship driven astern. The time for reversal of the ship follows an integral similar to eq. (23), only that B is given as difference of T and R rather than as sum as in eq. (20).

The retardation path h or the headreach of the ship can be derived from the definition of velocity $V = dh/dt$, giving the differential relation $dh = Vdt$.

Integrating, we obtain, with substitution of dt from eq. (22) and use of eq. (20),

$$h = \int V dt = -M \int \frac{V dV}{B} = \frac{kD}{A} \int_0^{V_n} \frac{V dV}{U_r^2 + U_r V + s_n(1 + s_n) V^2}. \quad (28)$$

This integral can be reduced to the one in eq. (23) by a well-known method

$$\int \frac{V dV}{\bar{B}} = \frac{\ln \bar{B}}{2 s_n (1 + s_n)} - \frac{U_r}{2 s_n (1 + s_n)} \cdot \int \frac{dV}{\bar{B}} \quad (29)$$

which easily can be evaluated between the limits 0 and V_n by eqs. (25a) or (25b).

For the discriminant $\Delta = 0$ or a slip $s_n = 20.7$ per cent., the value of eq. (28), with use of eqs. (20) and (26), is determined by

$$\int_0^{V_n} = 2 \left[\ln \left(1 + \frac{V_n}{U_r} + \left(\frac{V_n}{2 U_r} \right)^2 \right) - \frac{V_n / U_r}{1 + V_n / 2 U_r} \right]. \quad (30)$$

Thus, according to eq. (28), the dependence of the headreach on displacement D and area A of the propeller disk is generally the same as with eq. (23) for the stopping time, while the influence of the initial velocity V_n of the ship and of the reversed velocity U_r of the propeller column is somewhat different. For the same numerical example as before, we obtain a headreach according to eqs. (28) and (30),

$$h = \frac{0.8 \cdot 10{,}000}{19.6} \cdot 2 \left[\ln (1 + 2 + 1) - \frac{2}{1 + 2/2} \right] = 315 m,$$

which again refers to ideal conditions and to a normal slip of about 20 per cent. This headreach is about twice the length of a 10,000 metric ton ship.

Since the integral in eq. (28) is dependent only on the normal slip s_n and the ratio U_r / V_n, the magnitude of the headreach for other slips than 20 per cent. is also proportional to the quotient kD/A and therefore independent of the absolute value of the velocity V_n of the ship.

It is obvious from eqs. (27) and (28) that the area A of the propeller disk plays a major role in attaining small stopping time and small headreach. This area has also a bearing on the slip during normal drive ahead. Large propeller area effects a small normal slip s_n which makes the discriminant of eq. (24) negative. Thereby the integrals for time and headreach become smaller and thus the size of the propeller disk has a twofold influence on the backing properties.

The reversal of the propeller column to a velocity of half the normal ship velocity, $U_r = 1/2 V_n$, produces a reversed thrust T_r which is with a normal slip $s_n = 20$ per cent. about three times the normal thrust T_n of the propeller. This means a high overload of propeller and driving machinery in the reverse operation. Hence it is obvious that any

actual limitation in the reversal torque of the propeller motor will greatly restrict the backing and reversal effects of the propeller on the ship. From this point of view propulsion by reciprocating engines or by electric motors appears more favorable than propulsion by steam turbines with backing stages.

In case the propeller machinery is capable of sustaining the initial torque T_r during the retardation period of the ship, as indicated by the dashed line in Fig. 16, the standstill is reached more quickly and the headreach is shorter. This can be attained only by a steadily increasing reversed speed U of the propeller column, since in eq. (6) or (9) T has to be kept constant at decreasing speed V. The backing forces are now, instead of eq. (20),

$$\bar{B} = \bar{T}_r + \bar{R}, \tag{31}$$

where only R is dependent on V. Thus the stopping time becomes, corresponding to eq. (23),

$$t = \frac{kD}{A}\int_0^{V_n} \frac{dV}{\bar{T}_r + s_n(1+s_n)V^2} = \frac{kD}{AV_n}\frac{\sqrt{T_n/T_r}\cdot\tan^{-1}\sqrt{T_n/T_r}}{s_n(1+s_n)} \tag{32}$$

wherein, according to eq. (14), the normal thrust T_n is substituted for V_n where proper. The headreach under such constant backing thrust is, corresponding to eq. (28),

$$h = \frac{kD}{A}\int_0^{V_n} \frac{VdV}{\bar{T}_r + s_n(1+s_n)V^2} = \frac{kD}{A}\frac{\ln(1+T_n/T_r)}{2s_n(1+s_n)} \tag{33}$$

wherein again eq. (14) is substituted after the integration.*

At a constant backing thrust of three times the normal thrust, $T_r = 3T_n$, corresponding, according to Table 1, to a normal slip $s_n = 20.7$ per cent. as in our former example, we obtain for the same ship as before a braking time until standstill

$$t = \frac{0.8\cdot 10{,}000}{19.6\cdot 10.3}\frac{\sqrt{1/3}\cdot\tan^{-1}\sqrt{1/3}}{0.25} = 48 \text{ sec.},$$

and a headreach

$$h = \frac{0.8\cdot 10{,}000}{19.6}\frac{\ln 1.33}{2\cdot 0.25} = 234m.$$

These figures, of course, are smaller than those reached with linearly decreasing backing thrust and constant reversed speed of the propeller column. However, it is questionable whether the corresponding high overload of the propelling motor by both high torque and high speed is practicable.

* Similar formulae for retardation time and headreach under constant backing thrust have been derived in a discussion by R. H. Tingey.[19]

In actual operation the propeller does not reverse instantaneously, as we have assumed in the ideal diagram of Fig. 16. Therefore the backing thrust does not start suddenly at T_r, but drops gradually from the thrust ahead, T_n, during the time of propeller reversal, finally attaining a value near T_r. It follows exactly the fluctuating torque curve of Fig. 15, going down from T_n to zero and over T_b to T_0 and upward again towards T_r. Hence, as shown in Fig. 17, in the beginning range there is some deficiency from the full reversal thrust and therefore the time and the headreach during retardation will actually be slightly greater than expressed by the foregoing formulae.

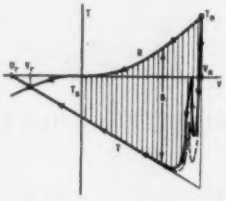

FIG. 17. Influence of the finite time of propeller reversal on the beginning of the ship reversal.

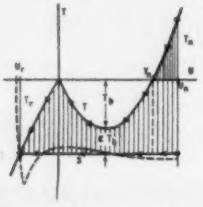

FIG. 18. Counteraction of motor thrust and backing propeller thrust at retardation of the propeller.

Ordinarily the reversal of the propeller and motor takes much less time than the reversal of the entire ship so that we may base its calculation on constant velocity V_n of the ship. The backing torque of the propeller machinery has to overcome the propeller torque developed by the water column during the reversal. Since torque and thrust are proportional for an ideal propeller, we can transform the backing torque of the machinery into a backing thrust S, which in Fig. 18 is plotted against the velocity U of the propeller column, which in turn is proportional to the propeller speed. Thus the diagram of Fig. 18 may represent in one scale of units thrust and velocity of the propeller column, and in another scale of units torque and speed of the actual propeller. The dashed line indicates the backing torque characteristic of the usual electric propeller motor.

We will assume, for the sake of simplicity, that the propeller is reversed by action of a constant reversal torque or thrust, S, of the

propelling machinery. The forces retarding the propeller are given by the sum of S and T, as shown by the shaded area of Fig. 18 where T for the most part is negative. They act on the inertia masses m related to the propeller or water speed U, causing a deceleration as determined by

$$-m\frac{dU}{dt} = S + T. \tag{34}$$

Let us define a starting time-constant of the rotating parts by the normal angular velocity ω_n of the propeller, the moment of inertia I of the rotating masses, and the normal torque Q_n, as

$$\frac{\omega_n I}{Q_n} = \tau = \frac{U_n m}{T_n}. \tag{35}$$

The same time constant can be defined by the parameters of the translatory movement of the water column as in the last term of eq. (35), namely by the normal column velocity U_n, the normal propeller thrust T_n, and the mass m equivalent to all the rotating masses on the propeller shaft. Thus the time constant τ and the equivalent mass m can be computed easily from the design data of machinery and propeller. Usually the time constant of propeller and motor is of the order of a few seconds.

The retarding time of the propeller as derived from eq. (34), with the equivalent mass m of eq. (35), is

$$t = -m\int\frac{dU}{S+T} = -\tau\frac{T_n}{U_n}\int\frac{dU}{S+T}. \tag{36}$$

If we substitute in numerator and denominator the specific thrusts according to eq. (9), we obtain, with use of eq. (2),

$$t = -\tau\frac{\bar{T}_n}{U_n}\int\frac{dU}{\bar{S}+\bar{T}} = -\tau s_n V_n\int\frac{dU}{\bar{S}-V_n U+U^2}. \tag{37}$$

This integral has to be taken between velocity U_n of the water column at full speed ahead and zero, if we compute the braking time of the propeller until standstill; and from zero to the reversed velocity U_r, with inverted sign of the analytical expression of T in the denominator, if we compute the time during actual reversal of the propeller.

For evaluating the integral in eq. (37) we denote by ϵT_b the necessary excess motor torque in comparison to the maximum backing torque T_b as seen in Fig. 18, so that ϵ is the relative excess of torque or thrust of the propelling machinery over the maximum torque or thrust produced by the propeller column during the retardation period. According to Fig. 18 and with use of eq. (15), we have for the constant motor thrust

in specific values

$$\bar{S} = \bar{T}_b + \epsilon \bar{T}_b = \frac{1+\epsilon}{4} V_n^2 \tag{38}$$

and the integral of eq. (37) can be evaluated to

$$-\int_{U_n}^{0} \frac{dU}{\frac{1+\epsilon}{4} V_n^2 - V_n U + U^2} = \frac{2}{V_n \sqrt{\epsilon}} \left[\tan^{-1} \left(\frac{1+2s_n}{\sqrt{\epsilon}} \right) + \tan^{-1} \left(\frac{1}{\sqrt{\epsilon}} \right) \right]. \tag{39}$$

The period for retarding the propeller so that its water column comes to a standstill is therefore, according to eq. (37),

$$t = \frac{2\tau s_n}{\sqrt{\epsilon}} \left[\tan^{-1} \left(\frac{1+2s_n}{\sqrt{\epsilon}} \right) + \tan^{-1} \left(\frac{1}{\sqrt{\epsilon}} \right) \right]. \tag{40}$$

As an example, with a time constant $\tau = 3$ sec., a normal slip $s_n = 20$ per cent. and an excess braking torque $\epsilon = 25$ per cent., we obtain a braking time

$$t = \frac{2 \cdot 3 \cdot 0.20}{\sqrt{0.25}} \left[\tan^{-1} \left(\frac{1.40}{0.5} \right) + \tan^{-1} \left(\frac{1}{0.5} \right) \right] = 5.6 \text{ sec.}$$

Thus the propeller is stopped in a period short as compared with the braking time of the entire ship.

This stopping time of the propeller depends on three parameters only, namely the starting time constant τ of the rotating masses, the normal slip s_n of the propeller during full speed ahead, and the relative excess torque ϵ of the machinery in backing operation; the first two are in the numerator, the last one in the denominators of the determining eq. (40). Small slip s_n shortens the retarding time more than proportionally. However, a considerable braking torque is needed for the same effect.

In actual operation it is hardly possible to maneuver the propelling machinery instantaneously from full driving torque to full backing torque. This operation needs some time and in the interval almost no torque will be exerted on the propeller. Therefore the propeller will quickly lose its slip and fall back to the ship's velocity, driving the ship for a very short period under the action of the rotating inertia masses only. This is indicated in Fig. 18 by the thrust triangle over the distance $U_n - V_n$. After the maneuvering interval, the backing thrust develops at the velocity V_n as shown by the dashed vertical line of Fig. 18. If this interval is long, the ship may have lost some velocity, which can be determined easily by integrating the resistance curve R of Fig. 16 alone. The period in which now the propeller column comes

to a standstill follows the previous integral, eq. (39), to be taken only between the limits V_n and o. This gives for the retardation period

$$t = \frac{4\tau s_n}{\sqrt{\epsilon}} \tan^{-1}\left(\frac{1}{\sqrt{\epsilon}}\right). \tag{41}$$

The numerical value is slightly smaller than that of eq. (40) and is $t = 5.3$ sec. in our example; however, the maneuvering times of the valves or circuit breakers have to be added, which often are considerably greater.

After actual reversal of the propeller, the time follows the same integral as in eq. (37), except that now we have to invert the sign of the thrust T as explained in section 3. We thus obtain for this period

$$t = -\tau \frac{\bar{T}_n}{U_n} \int \frac{dU}{S - T} = -\tau s_n V_n \int_0^U \frac{dU}{\bar{S} + V_n U - U^2} \tag{42}$$

with U having negative values. The limiting velocity $U = U_r$ is determined by the intersection of the two torque curves, as in Fig. 18, giving for U_r, with use of eq. (38), the conditional equation

$$\bar{T}_r = U_r(U_r - V_n) = \bar{S} = \frac{1 + \epsilon}{4} V_n^2. \tag{43}$$

Hence, since the denominator under the integral of eq. (42) eventually approaches zero, the time elapsing up to the intersection extends towards infinity, as is well known from similar examples with acceleration to an asymptotic limit.

The integral of eq. (42) can be evaluated, giving

$$t = \frac{2\tau s_n}{\sqrt{2 + \epsilon}} \left[\tanh^{-1}\left(\frac{1 - 2U/V_n}{\sqrt{2 + \epsilon}}\right) - \tanh^{-1}\left(\frac{1}{\sqrt{2 + \epsilon}}\right)\right] \tag{44}$$

and the curve of time versus velocity U thus can be plotted up to any desired approach to the asymptotic speed U_r. In order to obtain a definite nominal time of reversal it is suitable to extend such time to only 90 or 95 per cent. of the full propeller speed astern. Such reversal period is, in an actual example, generally in the same order of magnitude as the braking period of eq. (40).

If for any actual propelling machinery the torque-speed characteristic S is accurately given, as by the dashed curve of Fig. 18, deviating from the constant value here used, it is much more convenient, instead of any analytical evaluation, to integrate the curves of Fig. 18 graphically, in accordance with the general formulation of eqs. (37) and (42). Furthermore, it may be that the value of the contraction coefficient k is accurately known for an actual case, derived for example from tank experiments on a model propeller. Then we could cover graphically even a variability of k over the various ranges by taking k within the

integrals for computing the headreach and reversal times of propeller and ship.

5. ACTUAL PROPELLER TORQUE AND PROPELLER SPEED.

For performance of the integrations of the last section, perfect propeller action with 100 per cent. blade efficiency was assumed. The actual propeller, however, produces a thrust which is different from that of an ideal propeller, the ratio being given by $\eta' \leqq 1$. With use of the no-load pitch p of the propeller, defined by the no-thrust angle of the propeller blades, the actual thrust T can be correlated to the torque Q by

$$T = \eta' \frac{2\pi}{p} Q, \tag{45}$$

where η' represents a dynamic coefficient.

Similarly, the axial velocity of the water column produced by an actual propeller of the same pitch p is different from that of an ideal propeller in the ratio $\eta'' \leqq 1$. Thus the velocity of the water column is

$$U = \eta'' \frac{p}{2\pi} \omega, \tag{46}$$

where η'' represents a kinematic coefficient and ω is the propeller angular velocity. The power of the propeller is

$$P = TU = \eta' \eta'' Q \omega, \tag{47}$$

so that the product $\eta'\eta''$ is the efficiency of the propeller proper under actual driving conditions as distinct from the efficiency of the ship's propulsion, given in eq. (8). For backing conditions, where the thrust T produces the torque Q, the efficiency is $1/\eta'\eta''$.

The speed of the propeller in revolutions per second is, with use of eq. (46),

$$N = \frac{\omega}{2\pi} = \frac{U}{\eta'' p}. \tag{48}$$

Thus the propeller speed is proportional to the velocity U of the water column except for the influence of η''. However, η'', indicating a slip between propeller helix and water column, is mainly dependent on the thrust and thus, according to eq. (6) or (9), on the water velocities U and V. Therefore we can represent the correlation of η'' and the velocity U, at constant speed V_n of the vessel, by a curve as in Fig. 19. Always η'' is near the value 1 where thrust or axial load of the propeller are zero, and has a value smaller than 1 under driving conditions with $U > V_n$. For backing conditions, η'' follows the trend of the thrust curve, attaining values greater than 1 since here the water drives the propeller. For reversing conditions and negative speed U of the water

column, where the thrust increases rapidly with reversed propeller revolution, η'' will sharply decrease because of the unfavorable development of the streamlines around the propeller blades.

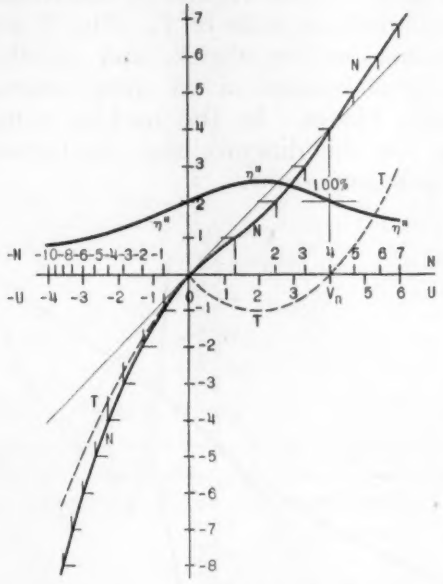

FIG. 19. Correlation of propeller speed and velocity of water column as determined by kinematic propeller coefficient.

Hence the propeller speed N, according to eq. (48), can be plotted easily as quotient of U and η'' versus U in a curve which also is shown in Fig. 19. From this curve we can now determine, correlated to the horizontal uniform scale of U, a scale for the propeller speed N which of course is not uniformly distributed along the horizontal axis. In order to obtain comparable values of N and U in the diagram, we drop the factor p of eq. (48) as unimportant for the scales. N coincides with U only for the column velocities $U = 0$ and $U = V_n$. For backing performance with U still positive the N-scale appears condensed towards V_n, and for reverse operation of the propeller its speed N increases much more rapidly than the negative U does.

A similar correlation develops between propeller torque Q and axial thrust T which is, according to eq. (45),

$$Q = \frac{pT}{2\pi\eta'}. \tag{49}$$

Also η' depends primarily on the thrust T. η' is nearly 1 at thrust zero, except for purely frictional forces. It slowly decreases with positive thrust but increases with negative thrust in the backing range,

and is shown in Fig. 20 as a curve referred to the vertical axis. In the reversing range η' decreases rapidly with negative thrust, forming another branch of the curve. The torque Q, determined by the quotient T/η', is shown in Fig. 20 as a curve, and is transferred to a scale correlated to the vertical uniform scale of T. The Q scale is compressed slowly with increasing positive thrust, and rapidly with increasing negative reversal thrust because of the more unfavorable water flow around the propeller blades. In the backing range the Q-scale is slightly expanding. In this diagram also, the factor $p/2\pi$ of eq. (49) has been dropped as unimportant.

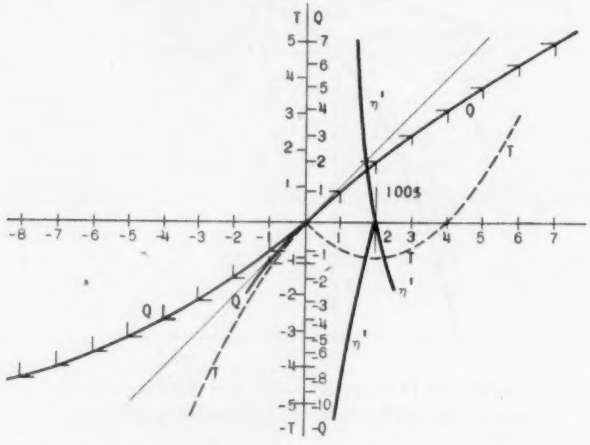

FIG. 20. Correlation of propeller torque and propeller thrust as determined by dynamic propeller coefficient.

The coefficients η' and η'' can be determined analytically only by consideration of the water flow within the zone of the propeller blades. This has been attempted by various investigators with considerable success for normal drive ahead.[4–6,21–23] In the backing and reversal ranges no attempt has succeeded so far. For an individual propeller the coefficients can be determined experimentally by measurement of the quotients U/N and T/Q at various positive and negative speeds. For reverse drive of the propeller the numerical values may easily decrease towards 50 per cent., depending entirely on the shape of the blades. If such tests are made with a model propeller in an experimental tank, the frictional losses should be included in the determination of the coefficients η. At the same time, the contraction coefficient k may be derived from measurements on the model propeller, thus increasing the accuracy of correlation between velocities and thrust, as mentioned in Sections 3 and 4.

For a more rigorous analysis of the propeller performance with respect to backing and reversing, we may either use the original sym-

metrical T-curve, as plotted in Fig. 21 in uniform T- and U-scales, thus giving torque and speed of the propeller in the condensing scales for Q and N, or we may, as shown in Fig. 22, replot this curve in uniform

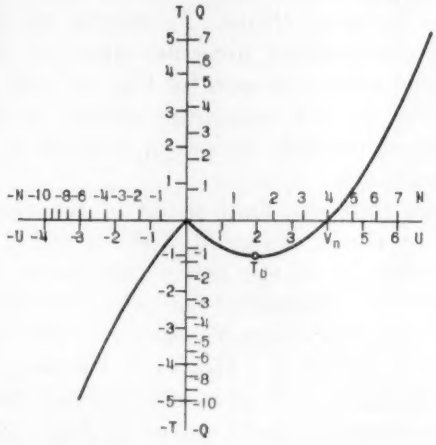

FIG. 21. Broken thrust-torque curve of propeller vs column velocity and propeller speed.

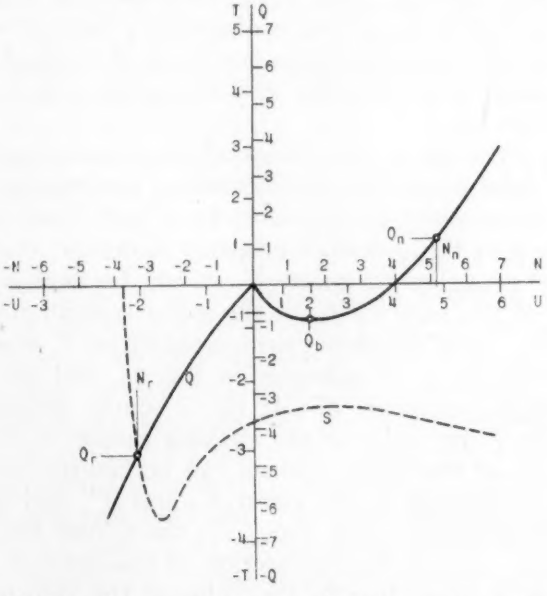

FIG. 22. Dissymmetrical torque-thrust curve of propeller vs propeller speed and column velocity.

scales of Q and N. Figure 21 is neater for a survey, because it contains only one parabolic curve for both thrust versus column velocity and torque versus propeller speed. Figure 22 is more convenient for

graphical integration of the propeller reversal, particularly if the torque-speed curve of the propeller machinery is given, as indicated by the dashed curve S. The two axes in Fig. 22 contain also scales for U and T which now appear expanding towards the larger values.

The maximum backing thrust T_b occurs at a column velocity $U = V_n/2$. The corresponding propeller speed N, however, is smaller than half the no-load speed, as seen by Fig. 21, due to the unequal N-scale. Hence in Fig. 22 the maximum thrust, or torque Q_b, appears substantially displaced towards the origin, a result in accord with many of the actual experiments.

Figure 22 shows that the final speed of reversal of the propeller, N_r, as determined by the intersection of the S and Q curves, produces a relatively low velocity U_r of the water column by effect of the small propeller coefficient η''. Therefore the actual thrust T is not as large as if we would identify the column velocity U directly with the motor speed N as is done in section 4. However, the shape of the Q-curve in Fig. 22, in the backing as well as in the reversal range, is not greatly different from the shape of the T-curve in Figs. 21 or 18, which we have used for integration over the backing and reversal periods of the propeller. Hence the results of our calculations for the propeller performance, eqs. (40) and (44), will provide us with a fair approximation. If, on the other hand, the coefficients η' and η'' are known for the actual propeller, and the torque curve of the actual motor also is known, then there is no difficulty in performing a rigorous integration by means of Fig. 22.

The thrust produced by the completely reversed propeller, retarding the vessel, as determined by eqs. (6) and (9) and represented by Figs. 13 and 16, is given solely by the velocities U and V and is independent of the efficiency of the propeller proper. However, if after complete reversal of the propeller its speed N_r should be kept constant by its machinery, then the velocity U_r of the water column actually will not remain constant. For, the slowly decreasing thrust T, as seen by Fig. 16, causes an increase in η'' as indicated in Fig. 23, and therefore a corresponding increase occurs in U. If the η''-curve dependent on T is known, then for every value of the backing thrust $-T$ in Fig. 23 the true velocity U_r of the water column can be determined according to eq. (48) by the product of the given N_r and η'', and plotted on the negative horizontal axis. For every U_r the thrust line is known by eq. (9) and Fig. 13 and the intersection of this straight line with the assumed thrust T gives directly the value of the velocity V to which this thrust T is correlated. Hence the actual T-curve can be plotted, as in Fig. 23, giving the true thrust versus velocity curve during reversal. Combined with the resistance curve R of the ship, the retardation time now can be rigorously integrated graphically according to the first term of eq. (23).

Should the propeller speed N_r be increased after complete reversal, as is often done with electric propulsion, there is no difficulty in computing in the same way for every instant the true end U_r of the straight thrust line on the negative abscissa of Fig. 23. A graphical integration thus can always be performed.

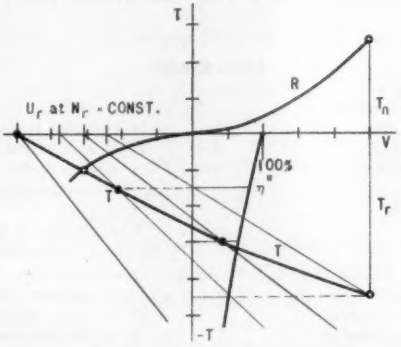

FIG. 23. Decrease of backing thrust during actual reversal of ship at constant propeller speed.

We see from Fig. 23 that the actual thrust T, by effect of the increasing propeller efficiency during backing and reversal of the ship, is somewhat larger than the T values in Fig. 16 which we had integrated analytically. This gives actually shorter times for the retardation, particularly for the reversal period. Hence, the results of our calculations of the performance of the entire ship, eqs. (25) to (27) and (28) to (30), provide us with a safe approximation.

SUMMARY OF PART I.

Thrust and torque of a propeller during stopping or reversal of a ship are known as widely different from those at normal drive ahead. By means of streamline patterns for the various ranges of operation a detailed analysis of the changing phenomena is developed which clarifies the mechanism of the production of the backing forces. This makes possible an analytical derivation of the actual thrust and its variation during the two transient periods of reversing the propeller and backing the ship. In contrast with the analytical formulation, the reactive forces of the propulsive jet do not change their direction on reversal of the propeller, giving the thrust-speed characteristic the shape of a broken parabola. The empirical results as published in the literature are in full agreement with the conclusions of the paper. The stopping times of both propeller and ship and the headreach minimally attainable are determined as depending on a few main data only of machinery, propeller and ship.

The general behavior of a screw propeller under the conditions of reversal is divided into a kinematic and a dynamic component, both showing clearly the deviation from the performance of an ideal propeller. This makes possible a simple scheme of accounting for the actual effect of the propeller blades and leads to the development of a graphical method for solving numerically the complete problem of reversal for any given example.

Letter Symbols.

a = area of propeller blades
A = area of propeller disk
b = mean blade thickness
B = backing force on vessel
c = drag coefficient
d = propeller diameter
D = displacement
E = kinetic energy
h = headreach
I = moment of inertia
k = coefficient of contraction
l = length of inertia cylinder
m = linear inertia mass
M = inertia mass of vessel
N = speed of propeller
p = pitch of propeller
p = pressure head
P = power of propulsion
Q = propeller torque
r = radius
r = wake fraction
R = water resistance of vessel
s = slip ratio
S = motor thrust
t = time
T = thrust of propeller
U = water velocity through propeller
v = velocity
V = velocity of vessel
W = wake velocity at propeller
Δ = discriminant of a function
ϵ = excess torque
η = propeller coefficient
η = efficiency
ρ = mass density of water
σ = effective slip ratio
τ = time constant
ω = propeller angular velocity

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High Vacuum and Deep Freezing Dry Penicillin.—TERRY MITCHELL. (*Power*, Vol. 88, No. 10.) Seldom has any new use of refrigeration become so important so quickly as the one now being applied to the making of penicillin.

This drug must be moisture-free or it won't keep. Sufficient heat to drive off the water cannot be used as this would kill the life of the penicillin. (The finished product is sealed and must be stored at 50 deg. F.)

The problem of removing the tremendous amount of water vapor at low temperature was solved in a novel manner by the National Research Corp., a Boston concern specializing in high vacuum operations. They designed, built and installed equipment that combines low temperatures (down to 75 deg. F. below zero) with the highest vacuum ever applied to commercial dehydration work (1/100 of one millimeter of mercury or less).

The full sized plant making penicillin by vacuum diffusion process was built by the Commercial Solvents Corp., at Terre Haute, Indiana, in just 160 working days. Several plants using similar equipment are in use elsewhere in this country, and four of them are being supplied to our ally, Russia, for drying blood plasma.

Concentration of extract from the vegetable mold is a story in itself, but after the penicillin is placed in bottles, each holding 100,000 units, it is first deep frozen. The bottles are then put on shelves in drying chambers, called "ovens." Pipes above the battery of ovens lead to vacuum pumps which are in two stages. Evaporation of the ice occurs without any melting: In fact the moisture "sublimes" with a refrigerating effect, and to hasten the process a low heat has to be added through hot water headers leading to the shelves.

A sloping shell in the vacuum line serves as a moisture freezer or condenser. It is jacketed with very cold ammonia from a booster system, and equipped with revolving blades for scraping off the condensed vapor that forms inside, as the low temperature and high vacuum are applied. The ice falls into an air tight vessel below; this is heavily insulated and is refrigerated, through a jacket, to keep the moisture from re-sublimating. A small area in the slanted shell suffices to handle a large cooling load. Under the intense vacuum, molecules of moisture race toward the cold surface with terrific speed. Frost deposits on the surface as fast as the blades of the scraper can sweep it into the chamber below.

This drying process was originally developed as a means of dehydrating foods without "cooking" them or destroying their flavor or vitamins. Thus color, even the form, of the food is retained. Moisture content is reduced to less than 1%, whereas the usual air drying methods leave about 5 to 10%. By adding cold water the food may be restored to its initial freshness in a few seconds, the moisture entering through the minute holes in the cells through which it had passed when sublimated.

R. H. O.

THE CHARGE EFFECT IN RELATION TO THE KINETICS OF PHOTOGRAPHIC DEVELOPMENT. III. THE ABNORMAL BEHAVIOR OF SULFITE-FREE CAUSTIC HYDROQUINONE DEVELOPERS.

BY

T. H. JAMES.

Communication No. 1036 from the Kodak Research Laboratories.

The rate of development by hydroquinone in the absence of sulfite is increased by the addition of some partially oxidized hydroquinone [1,2] or by the addition of quinone itself [3] to the solution. It is not known whether quinone itself can act directly as an accelerator, since the quinone undergoes dismutation in alkaline solution,[4,5,6] and development is accelerated by some product or products of the dismutation. The dismutation product or products may be entirely responsible or only partially responsible for the acceleration resulting from the addition of quinone. It has been observed, however, that the more stable homologues of quinone are much less effective than quinone itself in accelerating development by their respective hydroquinones,[7] and this suggests that the dismutation product is at least the more important accelerator.

The addition of oxidation product to a sulfite-free hydroquinone developer produces a general increase in development rate over a rather wide range of exposures, and the accompanying changes in photographic characteristics are usually minor. When, however, development of a low-speed film of moderate contrast is carried out in a hydroquinone solution of suitable composition and containing no oxidation product initially, the localized action of the oxidation product formed during development can result in a remarkable change in the photographic characteristics. The dependence of the gross rate of development upon the exposure is greatly accentuated, with the result that the photographic contrast obtained for intermediate stages of development is greatly increased, and the toe of the characteristic curve nearly vanishes at some stages. This abnormal course of development is of added interest because of its marked similarity to the development of Kodalith

[1] H. Staude, *Fot. Rundschau*, **72**, 390 (1935).
[2] H. Staude, *Z. wiss. Phot.*, **38**, 65 (1939).
[3] T. H. James, *J. Phys. Chem.*, **43**, 701 (1939).
[4] B. Scheid, *Ann. Chemie*, **218**, 227 (1883).
[5] O. Hesse, *Ibid.*, **220**, 367 (1883).
[6] A. E. Cameron, *J. Phys. Chem.*, **42**, 1217 (1938).
[7] T. H. James, *J. Phys. Chem.*, **44**, 42 (1940).

film in its special, formaldehyde-containing developer.[8] The "Kodalith characteristics," which are of importance in the successful use of the half-tone reproduction process, are generally obtained by the unique combination of the special film and the special developer.

The present paper will deal only with results obtained with the simple caustic hydroquinone developer used in combination with positive-type photographic films. It will be shown that the abnormal characteristics are the result of localized changes in the magnitude of the charge-barrier surrounding the silver halide grain, and that a variation in the induction periods of development of the individual grains is involved.

The photographic materials employed contained no optical sensitizer. The first, "C," was a normal motion-picture material having a medium distribution of grain sizes. The second, "G," likewise was a motion-picture material, but the distribution of grain sizes was narrow, and the material can be considered as having grains of relatively uniform size.[9] The film was exposed to light of uniform intensity, at a series of time steps varying by a factor of 2. Development was carried out at 20° C. in an atmosphere of oxygen-free nitrogen in an apparatus previously described.[3] The use of the inert atmosphere is essential. Silver determinations were made by potentiometric titration at 70° C. with 0.0010 *M* potassium iodide. The mass of silver is expressed in terms of milligrams per 100 sq. cm. of film.

The abnormal photographic characteristics of the sulfite-free hydroquinone developer were most noticeable when the developing agent was used in a caustic solution containing potassium bromide. Optimal results were obtained with a solution of the following composition: Hydroquinone, 0.005 *M*; potassium hydroxide, 0.05 *M*; potassium bromide, 0.0067 *M*. The solid curves in Figure 1 show a typical result. Here, the optical diffuse density is plotted against the logarithm of the exposure, to give the photographic "characteristic curve." Of particular interest is the very short toe and subsequent steep ascent of the 6- and 8-minute curves at the low-exposure end. The maximum slope for the 8-minute curve is seven or greater—roughly double the maximum obtained for complete development. The abnormal behavior of the developer at this stage is also quite apparent when the progress of development is watched under the illumination of a No. 0 Wratten safelight. At the very start of development, the first traces of image appear quite normally, and nothing unusual is observed in the progress of development of the first few exposure steps (corresponding to the higher exposures). After a few minutes, however, the steps corresponding to lower exposures begin to appear, and these appear quite suddenly, one after another, each step developing to a considerable

[8] Cf. J. A. C. Yule, J. FRANK. INST., **239**, 221 (1945).

[9] T. H. James, J. FRANK. INST., **240**, 83 (1945).

density before the next one appears. Just before each of these steps begins to develop as a whole, development appears to "sweep over" the border from the adjacent developing (higher exposure) step.

Abnormality of the type described, but less marked in extent, has been obtained in less alkaline solution, even at pH as low as 8.8. The presence of some soluble bromide in the developer is essential to any marked effect, even at the highest pH. In the caustic solution, little

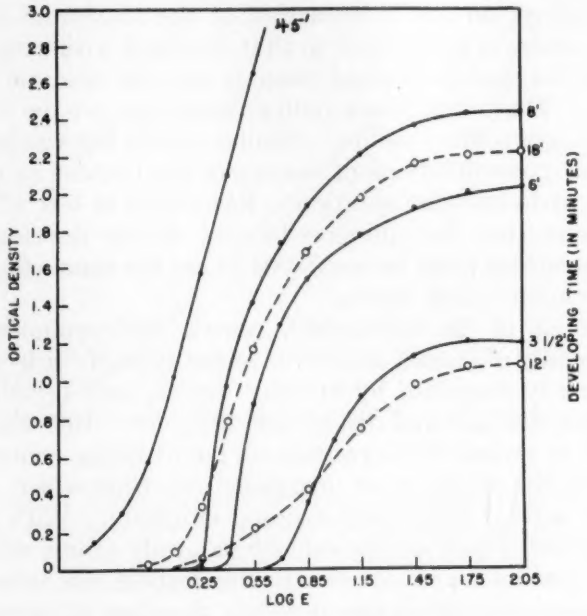

FIG. 1. Characteristic curves for development of film "G" in caustic hydroquinone solution, showing abnormality obtained in absence of sulfite (solid curves) and the more normal shape in the presence of 5 g. Na_2SO_3 per liter (broken curves).

difference was noted for bromide-ion concentrations varying from 0.003 to 0.03 *M*. When, however, no bromide was added to the solution and the film was given a preliminary washing to eliminate soluble bromide from that source, the development characteristics of the caustic hydroquinone solution showed only slight departures from those of a conventional developer.

Abnormal development of the type described can be obtained with certain other sulfite-free developers, such as chlorohydroquinone, bromohydroquinone, and *p*-hydroxyphenylglycine. These agents do not give so pronounced an effect, however. Toluhydroquinone shows some abnormality, xylohydroquinone practically none. In the latter two cases, however, excessive fog formation enters as a possible complicating factor.

A connection between the peculiarity of the caustic hydroquinone development and the oxidation product formed during that development can readily be demonstrated. The quinone formed initially will be quickly and almost quantitatively removed if the solution contains sufficient sodium sulfite. Under such circumstances, the caustic hydroquinone solution shows no abnormality. The dotted curves of Figure 1 show the effect of adding 5.0 grams of sodium sulfite to a liter of caustic hydroquinone solution. The sulfite has produced a considerable extension of the toe region and a reduction of the maximum slope. The shape of the curves is fairly close to that obtained with such "normal" developers of the doubly-charged class as ascorbic acid and potassium ferro-oxalate. The slight abnormality remaining can be removed by further addition of sodium sulfite. Similar results likewise are obtained when sufficient concentrations of resorcinol are present in the (sulfite-free) caustic hydroquinone solution. Resorcinol is less efficient than sulfite in eliminating the quinone formed during development, and larger concentrations must be employed to get the same effect upon the shape of the characteristic curve.

The behavior of the sulfite-free, caustic hydroquinone developer shows some points of formal similarity to the type of "infectious development" recently described by Stauffer, Smith, and Trivelli.[10] There is an important fundamental distinction, however. Infectious development spreads to grains which contain no latent-image centers, and can even spread to the grains of an unexposed emulsion which is placed in close contact with a developing exposed emulsion. With the caustic hydroquinone developer, on the other hand, only grains which contain latent-image centers are involved. In this respect, the behavior of the caustic hydroquinone developer parallels the case of development of Kodalith film in the formaldehyde-hydroquinone developer, as described by Yule.[8] The effect is produced not by fogging grains in the vicinity of a developing grain, but by *increasing the rate of initiation of development* of such neighboring grains as are already developable, but have not yet passed the induction period stage. If development in the caustic solution is continued to completion, a perfectly normal characteristic curve is obtained (see curve marked 45 minutes, Fig. 1). Moreover, for a given exposure, the density obtained by maximum development is practically the same as that obtained by maximum development with diaminodurene, ferro-oxalate, or a normal high-speed elon-hydroquinone developer of the D-19 type.[11] The present phenomenon, therefore, does not involve "infectious development" in the sense in which the term is used by Stauffer, Smith, and Trivelli.

Basically, the abnormal behavior of the caustic hydroquinone developer is simply another manifestation of the charge effect. This is

[10] R. E. Stauffer, W. F. Smith, and A. P. H. Trivelli, J. FRANK. INST., **238**, 291 (1944).
[11] T. H. James, J. FRANK. INST., **239**, 41 (1945).

shown both by the sensitivity of the abnormality towards the bromide-ion concentration in the developer and by the fact that agents which accelerate development through depression of the bromide barrier (e.g., phenosafranin, pinacyanol, and thallous ion) eliminate or markedly reduce the abnormality (cf. Fig. 2).

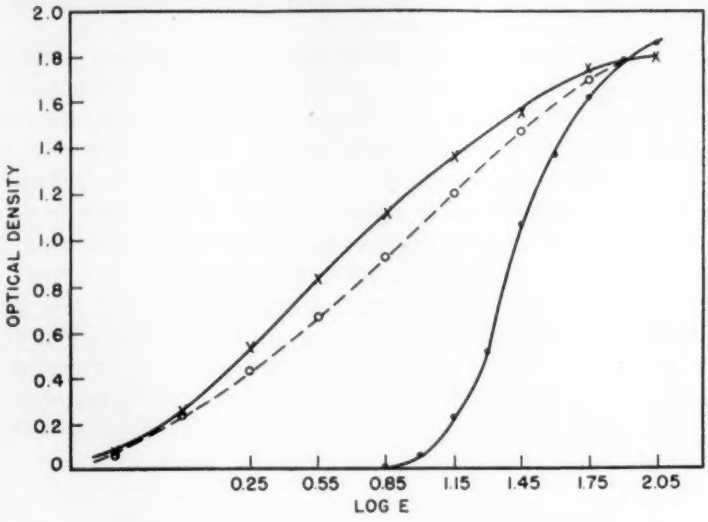

FIG. 2. Effect of sulfite and phenosafranin on the shape of the characteristic curve obtained by development of film "C" in caustic hydroquinone solution. —·—·— Simple caustic developer; --o--o-- same, with addition of 16.5 g. Na_2SO_3; —×—×— sulfite-free developer containing 0.0143 g. phenosafranin per liter.

The following mechanism is in accord with the observed facts. Some product arising from the oxidation of the hydroquinone (probably some product of the dismutation of quinone) accelerates development by depressing the bromide barrier through adsorption to the silver bromide surface. Such action, as already shown,[3,9] is most pronounced in the induction-period stage of development of the individual grains. At the high exposure levels, and for the photographic materials employed here, it has been shown [4,9] that the induction periods of the various individual grains do not differ significantly when the developer contains no added bromide. At the lower exposure levels, however, and particularly with developers containing bromide, this is no longer true.[12] The induction period varies significantly among the individual grains at a given exposure step. The grains with short induction periods soon pass into the stage of rapid development in the caustic hydroquinone developer. Some of the accelerating material formed in the process spreads to neighboring grains which normally have con-

[12] Cf. S. E. Sheppard and A. P. H. Trivelli, *Proc. 7th International Congress of Photography (London)*, p. 174 (1928).

siderably longer induction periods. These grains then quickly pass through the induction period, and quinone formed during subsequent development may increase the rate of initiation of development of yet other neighboring grains. Only those grains which contain latent-image centers will be affected, however, since this type of action does not promote fog to any appreciable extent. There will be no "infectious development" of significance.

If the initial bromide barrier is high, the localized action of the accelerating agent will result in a very sharp differentiation between two areas of the film which differ only slightly in exposure, provided development is stopped at the right point. If, however, the bromide barrier is decreased uniformly over the entire film, the localized drop produced by the accelerating agent formed during the development process has relatively much less effect upon the local development rate, and the differentiation between the adjacent exposure steps becomes less marked. Whereas sulfite and resorcinol remove the abnormal differentiation by removing the quinone, and thus preventing the localized action, phenosafranin and similar agents remove the abnormality by uniformly depressing the bromide barrier and thus removing the basis for the action of the accelerating agent. Oxidized hydroquinone, *present at the start of development*, acts in much the same way as phenosafranin.

DISTRIBUTION OF INDUCTION PERIODS.

A variation in the magnitude of the induction period of the individual grains of a normal positive-type material definitely exists in the medium and lower exposure ranges. This had been ascertained for normal development by microscopic examinations and by photometric equivalent determinations. For example, Sheppard and Trivelli [12] observed that both the number of developing grains and the average size of the silver particles increased with increasing development time. Sheppard and Mees had made similar observations in their classic investigations.[13] Determinations of the photometric equivalent by Sheppard and Ballard pointed to similar conclusions.[14] In the present case, important variations in the individual induction periods can be demonstrated by the same methods[9] as those previously employed to show that no important variation occurred in the high exposure region (corresponding to the shoulder portion of the characteristic curve where the slope is approaching zero).

Figure 3 gives a logarithmic plot of silver against density for film "G." Curve 1 is the straight line of slope 0.99 obtained when the average size of the developed grain, $\bar{a}$, was kept constant and only the

[13] S. E. Sheppard and C. E. K. Mees, "Investigations on the Theory of the Photographic Process," p. 75 ff., Longmans, Green, and Co., London, 1907.

[14] S. E. Sheppard and A. Ballard, J. FRANK. INST., **206**, 659 (1928).

number of grains per unit area, k, was varied. To achieve this condition, the film was given full exposure and development, and k was varied by using a series of films coated with different amounts of the silver halide, but at constant thickness maintained by appropriate addition of gelatin. Curve 2 represents approximately the condition where k is kept constant and $\bar{a}$ is varied. Film "G" of normal coating

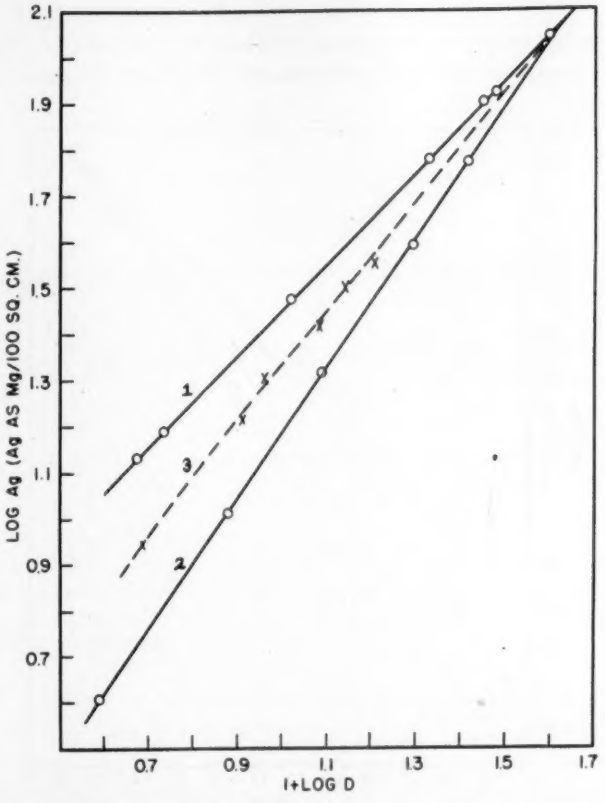

FIG. 3. Density-silver relationships for film "G". Curve 1, $\bar{a}$ constant, k varying; Curve 2, k approximately constant, $\bar{a}$ varying; Curve 3, development of log E = 0.55 step in caustic hydroquinone solution.

was given a high exposure and was developed for varying times in a sulfite-free, bromide-free hydroquinone developer of pH 8.8. Under these conditions, independent evidence has shown[9] that the individual grains are developing substantially in parallel fashion, so that k remains nearly constant and the density increases primarily by increase in $\bar{a}$. The slope of this straight line is 1.43, reasonably close to the value of 1.5 expected if k were strictly constant.[7] Curve 3 gives the results obtained by development in the caustic hydroquinone solution of the

exposure step corresponding to log $E = 0.55$. This curve lies in between 1 and 2, and its slope varies within the limits of 1.1 to 1.3. (The rather large scatter of the points probably results from local variations within the areas taken for silver analysis.) Hence, the increase in density is produced by both an increase in $\bar{a}$ and in k. Similar data for the maximum exposure step (log $E = 2.05$), on the other hand, gave a nearly straight line of slope 1.39, indicating much less variation in k.

Photometric equivalent determinations of samples of film "G" developed in a normal elon-hydroquinone solution of the composition

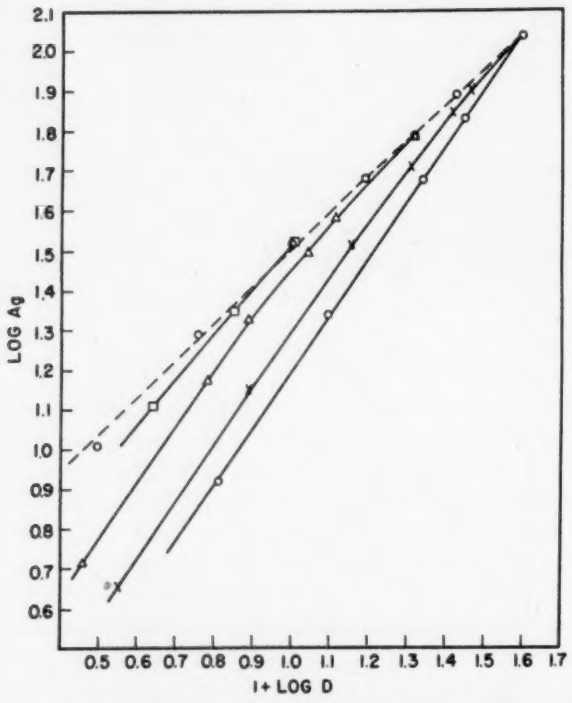

FIG. 4. Density-silver relationships for film "G" developed in conventional elon-hydroquinone developer. --o--o-- maximum development, exposure varied; —o—o— development time varied, log $E = 1.75$; —×—×— log $E = 0.85$; —△—△— log $E = 0.40$; —□—□— log $E = 0.10$.

used in previous work on maximum development [11] show that much the same situation exists in that case (Fig. 4). At high exposures, the increase of density with time of development results primarily from an increase in the average size of the developed silver particles. At lower exposures, both size and number of particles become important variables. At the lowest exposure employed, the number of particles is the more important variable, although the average size still varies.

In this latter case, however, the dispersion in the individual induction periods must be quite large.

The variation in the individual induction period likewise may be shown by starting development in a bromide-free hydroquinone solution of pH 8.8 and observing the effect of bromide added at various stages of development. (The caustic hydroquinone solution is not satisfactory for this purpose, since it produces excessive fog in the absence of bromide.) Figure 5 gives data obtained with film "G," exposed at

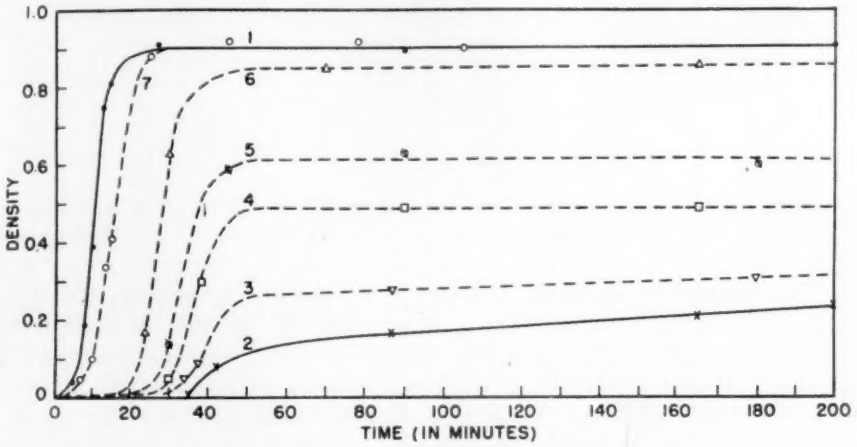

FIG. 5. Effect of bromide added at various stages of development in hydroquinone solution of pH 8.8. Log E = 0.25. Curve 1, no bromide added; Curve 2, bromide added before start of development; Curve 3, bromide added after 0.25 min.; Curve 4, bromide added after 0.50 min.; Curve 5, bromide added after 1.0 min.; Curve 6, bromide added after 1.75 min.; Curve 7, bromide added after 4.75 min.

log E = 0.25. Curve 1 shows the change of density with time of development in the bromide-free solution. Curve 2 shows the results obtained when the solution contained 0.001667 M potassium bromide throughout the entire course of development. Curve 3 represents the data obtained when development was started in the bromide-free solution and the bromide was then added after development had proceeded for 0.25 minute. Curves 4, 5, 6, and 7 represent the data obtained when the bromide was added after development had proceeded in the bromide-free solution for 0.5, 1.0, 1.75, and 4.75 minutes, respectively. All data are corrected for fog, although in most cases the correction involved was very small.

In the absence of bromide, development proceeds to a well-defined maximum. If development is allowed to proceed for more than 2 minutes in the bromide-free developer, subsequent addition of the bromide changes the rate of development somewhat, but has no effect upon the maximum density obtained. When the bromide is added at 1.75 min-

utes, however, a small but definite decrease in maximum density is noted. The decrease becomes more marked the shorter the time of initial development. The magnitude of the effect also varies with exposure (Table I).

TABLE I.

Variation of Density with Time of Addition of Bromide.
Densities Measured after 90 Minutes' Development. Film "G".

KBr	Addition at (min.)	Log E				
		1.90	0.85	0.55	0.25	0.05–1
None	—	3.72	2.80	1.89	0.90	0.255
0.00167 *M*	4.75	—	2.80	1.89	.90	.245
.00167 *M*	1.75	—	2.75	1.82	.85	.16
.00167 *M*	1.0	—	2.68	1.625	.62	.10
.00167 *M*	0.5	—	2.49	1.465	.49	.05
.00167 *M*	.25	—	2.14	1.10	.28	.01
.00167 *M*	0	3.73	2.05	0.95	.17	.01

The change in maximum density, as shown by Figure 5 and by Table I, is brought about by a change in the *number* of completely developed grains. This is shown by photometric equivalent determinations. From the previous discussion of the density-silver relationship, it follows that when the size remains constant and the number changes, the photometric equivalent (Ag/D) remains essentially constant. When, however, the number remains constant and the size changes, the ratio should change approximately as the square root of the density. Table II shows that, in the present case, the photometric equivalent remains essentially constant for constant exposure. Hence, the decrease in density caused by the addition of bromide is not the result of a shift in any equilibrium process, but of an actual destruction of developability of some of the grains.

The destruction of developability is caused by quinone formed during the development process.[7] The destruction is complete, since subsequent bathing of the film in high-activity developers of normal composition does not result in significant further increases in density. In order to prevent development the quinone must effectively destroy all silver centers to which the developer has access in a given grain. In the hydroquinone developer of pH 8.8, this happens only when the centers are very small, since even moderate additions of quinone will not destroy the developability of the more highly exposed grains.

In the present experiments, the destructive action of the quinone is the means of demonstrating the variation in induction periods among the developable grains in the lower exposure regions. In the absence of bromide, a definite group of grains develop to completion for a given exposure, but the number of grains in this group is smaller than the

TABLE II.

Silver-Density Relationship for Maximum Densities.

Log *E*	KBr added at (min.)	*D*	10Ag/*D*
0.70	—	2.36	0.129
.55	—	1.92	.132
.40	—	1.37	.133
.25	—	0.96	.132
.10	—	.575	.134
1.00	0.00	2.70	.129
0.85	0.00	2.14	.129
.55	0.00	1.02	.134
.40	0.00	0.55	.137
0.85	0.50	2.52	.131
.55	.50	1.49	.129
.25	.50	0.52	.136
.85	4.75	2.81	.129
.55	4.75	1.91	.132
.25	4.75	0.945	.136
.10	4.75	.555	.130

number which would develop in the "maximum-speed" developers (e.g., hydroquinone or diaminodurene in caustic solution, ferro-oxalate, or D-19) described in a previous paper.[11] The difference between the two numbers represents grains in which developability has been destroyed. This can be shown by transferring strips of film, fully developed in the hydroquinone solution of pH 8.8, to a maximum-speed developer, such as D-19. No further increase in density occurs, except for that which corresponds to fog formation, showing that grains which originally were developable in D-19 are now no longer developable. The developability was destroyed by quinone formed during the reduction of adjacent grains, as shown by a series of control tests. It follows that reduction of some of the grains in the hydroquinone solution of pH 8.8 must have got well under way before development of others had reached the stage where quinone could no longer effectively destroy the development centers. This, in turn, implies a difference in the induction periods of the two groups.

A variation of induction periods exists even within the group which develops to completion. This is shown by the experiments in which bromide is added. If development is continued for more than 2 minutes in the bromide-free solution, development of all the grains in the group will have proceeded far enough so that the subsequent addition of bromide will not change the number of the grains which develop to completion. If the bromide is added at 1.75 minutes, however, the number will be somewhat smaller. Development of some of the grains will not yet have reached the point of immunity towards the action of the quinone. If the bromide is added at still shorter times, still fewer

grains will develop to completion. Thus, a definite variation over a range of about 2 minutes appears in the individual induction periods of the particular group of grains under discussion. In these experiments, the added bromide probably aids in the differentiation primarily by increasing the induction periods of the grains in which development has not proceeded very far. This gives the quinone a better chance to destroy the silver nuclei before they become too large.

ROCHESTER, N. Y.,
May 21, 1945.

NOTES FROM THE NATIONAL BUREAU OF STANDARDS.*

CRYSTALLIZATION PHENOMENA IN RUBBER.

An article on crystallization in natural and synthetic rubbers has been prepared by Leonard A. Wood of the Bureau for publication as a chapter in the book entitled "Advances in Colloid Science" now being edited by H. Mark and G. S. Whitny. As Dr. Wood explains, crystallization may be studied by a number of different methods. These include volume changes, thermal measurements, X-ray diffraction, optical double refraction, light transmission, and a study of mechanical properties such as modulus and hardness, or those evident in flow. Crystallization may occur in natural rubber, balata, gutta percha, chloroprene polymers (Neoprene), organic polysulfides (Thiokol), isobutene polymers (Vistanex and Butyl rubber), polyethylene, and in vinylidene chloride polymers and copolymers (Saran). Experimental results, together with a certain amount of interpretation, are presented regarding rate of crystallization, melting of crystals, change of melting range with temperature of crystallization re-crystallization, fraction of material in the crystalline state, and the effects of vulcanization on vulcanization on crystallization. While a certain emphasis is placed on work carried out at the Bureau, the chapter is intended as a summary of the field and contains over 140 references to the literature.

* Communicated by the Director.

MASS SPECTROMETRIC ANALYSES OF HYDROCARBONS.

The analyses of complex hydrocarbon mixtures can be made on the mass spectrometer with a high degree of precision. As explained by A. Keith Brewer and V. H. Dibler in the August *Journal of Research* (RP 1664), the basis for the analyses lies in two parenthetic facts: First, that molecules of all hydrocarbons when bombarded by 50 to 100 volt electrons are not only ionized but are broken down into every possible disintegration fragment; and second, that while the appearance ratios of these fragments is always the same for a given hydrocarbon, the ratios are never the same for different hydrocarbons.

A mass spectrometer record for any hydrocarbon consists of a series of peaks, the heaviest being for that of the normal molecule while the rest of the peaks are for the various possible fragments resulting from a loss of hydrogen atoms or C atom groups. The mass spectrometer

record for a mixture of hydrocarbons is the sum of the peaks for the various constituents wherein each contributes in exact proportion to the amount present in the mixture. The analysis of such a composite record consists in subtracting the contributions of each possible constituent. Mixtures containing over twenty compounds have been precisely analyzed at the Bureau.

The reproducibility between individual analyses is high. Almost invariably independent analyses will agree to within a few tenths to a few thousandths of one per cent. for the concentration of each component. The absolute accuracy, however, may or may not be as great as the reproducibility. While it is dependent on the reproducibility it is also dependent on the purity of the materials used for calibration and on a number of other factors which are not necessarily constant from day to day. In test analyses where the composition of the sample is known, the precision has been found to agree to within the limits of uncertainty in the sample.

The mass spectrometer uses about 0.01 ml of gas during an analysis. Although the smallness of sample required is often of great help, it does introduce a complication in the taking of representative samples. Indeed it is often evident that the reproducibility of the instrument is limited materially by non-uniformities in the sample.

HEATS OF COMBUSTION AND ISOMERIZATION OF ALKYLBENZENES.

In the August number of the *Journal of Research* (RP 1665), new experimental data on the heats of combustion and isomerization of the eight C_9H_{12} alkylbenzenes are reported by Walter H. Johnson, Edward J. Prosen, and Frederick D. Rossini of the Bureau's thermochemical laboratory.

The heats of isomerization of the eight C_9H_{12} alkylbenzenes were determined by measuring the ratios of the heats of combustion in the liquid state of purified samples of these compounds, using the procedure previously described for the hexanes, heptanes, and octanes. The data yield the following values for the heat of isomerization in the liquid state at 25° C., $\Delta H°$, of n-propylbenzene into each of the C_9H_{12} alkylbenzenes, in kcal/mole: n-propylbenzene, 0.00; isopropylbenzene, -0.67 ± 0.16; 1-methyl-2-ethylbenzene, -1.93 ± 0.16; 1-methyl-3-ethylbenzene, -2.48 ± 0.19; 1-methyl-4-ethylbenzene, -2.74 ± 0.26; 1,2,3-trimethylbenzene, -4.83 ± 0.22; 1,2,4-trimethylbenzene, -5.61 ± 0.16; 1,3,5-trimethylbenzene, -6.00 ± 0.26. These data were combined with the value previously reported for the heat of combustion of n-propylbenzene to obtain values for the heats of combustion of each of the C_9H_{12} alkylbenzenes in the liquid state at 25° C.

EFFECT OF HEAT ON PORTLAND CEMENTS CONTAINING VINSOL RESIN.

The use of air-entraining cements is rapidly increasing, principally because of their superior resistance to freezing and thawing. One agent commonly used to produce air entrainment is Vinsol resin. Some mills have experienced considerable loss of resin while grinding the flake or powdered material with clinker. This has occurred most frequently when high temperatures (around 300° F.) existed. Leonard Bean and Albert Litvin, of the Bureau, have conducted a study of the effect of heat on Vinsol resin and on its air-entraining properties. Vinsol resin was found to carbonize on heating at 300° F. Heating cement containing the resin for 48 hours at that temperature volatilized as much as two-thirds of the resin and reduced the air entrained by mortars made from the cement. Also, the methoxyl content of Vinsol resin was found to be reduced by heating at 300° F. Heating takes place in the finish grinding of commercial cements and temperatures of over 250° F. may be found after many days of storage. Methods of determining Vinsol resin are discussed.

FIRE TESTS OF TEMPERED GLASS.

Tempered or case-hardened plate glass is preferred to untempered glass in many locations on account of greater strength, and also to wired glass on the score of appearance. While not intended for use in fire protectives for openings in the same manner as wired glass, the reaction of tempered glass to fire exposure is of interest from the standpoint of hazard from flying fragments.

Tests at the Bureau indicated that plain glass will begin to fracture as soon as the flame touches it, with jagged pieces falling out without scattering. Tempered glass cracks suddenly after a few minutes of fire exposure into small granular pieces without sharp edges that are projected to considerable distances. In the case of wired glass, although it cracks, no pieces are dislodged and it remains as a fire barrier for 30 minutes or more of fire exposure until it melts, softens, or sags under its own weight.

EFFECTS OF COMBINED STRESSES AND LOW TEMPERATURES ON THE MECHANICAL PROPERTIES OF NON-FERROUS METALS.

By means of tension tests of notched specimens, D. J. McAdam, Jr., G. W. Geil, and B. W. Mebs have investigated the mechanical properties of K-Monel metal, nickel, plain and leaded phosphor bronzes, commercial aluminum, and high-purity aluminum. Diagrams have been drawn to show the influence of notches and of the stress system on resistance to plastic deformation, resistance to fracture, and ductility between room temperature and − 188° C.

The quantitative variation of mechanical properties with temperature has also been studied. For the above mentioned metals, the ductility does not decrease with decrease of temperature to − 188° C.

The correlation between ductility and stress-temperature lines for yield stress, ultimate stress, and initial technical cohesion limit is discussed in a paper that has been prepared for publication in the Transactions of the American Society for Metals.

THIN-WALLED ALUMINUM GEIGER-MÜLLER COUNTERS.

Geiger-Müller tube counters, consisting of an insulated wire mounted axially in a metal tube which is maintained at a potential several hundred volts from that of the wire, are useful in the measurement of beta radiation from radioactive substances. The tube counter is sensitive to very low intensities of beta radiation since it records each beta particle that passes through it by producing an electrical pulse which can be amplified and registered. The application of Geiger-Müller tube counters to the measurement of beta rays is restricted by the fact that beta rays with energies as high as 1,000,000 volts can penetrate only a fraction of an inch of ordinary materials. This means that the counter tubes must have walls which are very thin and of low density. Most previous attempts to achieve this have been laborious and expensive since the tube counter must be gas tight. By using methods to plate thin layers of copper on commercially available aluminum tubes, such as are used for toothpaste, Burrell W. Brown and L. F. Curtiss have found it possible to make very excellent thin-walled counters by soldering a metal plug in the open end of the toothpaste tube. As described in the *Journal of Research* for August (RP 1666), these plugs support the insulators and glass tube for filling and sealing. The walls are only 0.004 inch in thickness, which permits most beta rays to pass through and be recorded. Counters made in this way are relatively inexpensive.

THE FRANKLIN INSTITUTE.

LIBRARY NOTES.

The Committee on Library desires to add to the collections any technical works that members would wish to contribute. Contributions will be gratefully acknowledged and placed in the library. Duplicates received will be transferred to other libraries as gifts of the donor.

Photostat Service. Photostat prints of any material in the collections can be supplied on request. Orders received in the morning are filled the same day. The average cost of a print 9 × 14 inches is thirty-five cents.

The library and reading room are open on Mondays, Tuesdays, Fridays and Saturdays from nine o'clock A.M. until five o'clock P.M., Wednesdays and Thursdays from two until ten o'clock P.M.

RECENT ADDITIONS.

AERONAUTICS.

Great Britain. Air Ministry. Air Navigation. Volume 1. 1944.
PIERCY, N. A. V. A Complete Course in Elementary Aerodynamics. 1944.

BIOCHEMISTRY.

THOM, CHARLES, AND KENNETH B. RAPER. A Manual of Aspergilli. 1945.

BIOGRAPHY.

GAUL, HARRIET A., AND RUBY EISEMAN. John Alfred Brashear. 1940.

CHEMISTRY AND CHEMICAL TECHNOLOGY.

Society of Chemical Industry. Reports of the Progress of Applied Chemistry. Volume 28. 1943.
STEWART, ALFRED W., AND CECIL L. WILSON. Recent Advances in Physical and Inorganic Chemistry. Seventh Edition. 1944.

ENGINEERING.

PARKINSON, A. C. Engineering Inspection. Second Edition. 1944.
SWIFT, H. BEVAN. Principles of Magnetic Crack Detection. 1944.

MATHEMATICS.

PIZÁ, PEDRO A. Fermagoric Triangles. 1945.

MECHANICAL ENGINEERING.

National Physical Laboratory. Metrology Department. Notes on Gauge Making and Measuring. 1943.
LICHTWITZ, OTTO. Indexing and Spiral Milling. 1944.

METALLURGY.

GREGORY, EDWIN, AND ERIC N. SIMONS. Steel Manufacture Simply Explained. Third Edition. 1944.

NOTES FROM THE BIOCHEMICAL RESEARCH FOUNDATION.

Abstract of **The Electrophoretic Analysis of Stored Liquid Human Plasmas.**—LAURA E. KREJCI, LUCILE SWEENY, AND EDWARD B. SANIGAR (*Journal of Biological Chemistry*, **158**: 693, 1945). Pooled human plasma, prepared under sterile conditions by the closed vacuum technique and containing 5 per cent. of glucose and 0.01 per cent. of merthiolate, was examined by electrophoresis in the Tiselius apparatus after storage in the liquid state at room temperature for 3 years. There was a large increase of α-globulin at the expense of all the γ-globulin, all the fibrinogen, and part of the β-globulin. The mobilities were 20 to 25 per cent. greater than in fresh plasma, and the boundaries were broadened.

Heat treatment of fresh human plasma also caused an increase of the α-globulin, but at the expense of different plasma constituents, and without increase of the mobilities or broadening of the boundaries.

The addition of 5 per cent. of glucose to fresh human plasma produced an increase of the α_2-globulin at the expense of the β-globulin, with partial fusion of the α_2- and β-globulin boundaries in the negative arm; it also caused the disappearance of the α_1-globulin as a separate boundary. The former change persisted after removal of the glucose by dialysis; the latter did not. The electrophoretic patterns of plasmas stored at room temperature for periods of less than a month, with and without the addition of glucose, indicated protective action by the added glucose.

BOOK REVIEWS.

ELECTROMAGNETIC ENGINEERING, by Ronold W. P. King. 580 pages, illustrations, 14 × 22 cms. New York and London, McGraw-Hill Book Company, Inc., 1945. Price $6.00.

This is a subject in which there have been many different interpretations. Yet throughout its history, this has been good, as the results in a practical way show. From the purely mathematical point of view, the combined achievements of its history form a single, powerful tool for predicting pointer readings in intricate electrophysical and electrotechnical experiments. The analysis of practical problems based on fundamental theory has given great results from the physical angle.

The book at hand is the first of a series of three designed to follow the subject matter presented at the Cruft Memorial Laboratory at Harvard University. It therefore is an introduction, designed to provide the physical and mathematical background prerequisite to the systematic study of such fields as antennas and wave propagation, transmission circuits including wave guides, and transit-time electronics with application to microwave generators which are the subjects of later volumes. A working knowledge of calculus and of complex algebra, and some familiarity with elementary differential equations, are presupposed. Some knowledge of alternating currents is desirable.

The work opens with the vector-analytical description of the electrical properties of matter. Along with the definition of the four essential density functions in general form, the fundamental postulate of conservation of electric charge is expressed mathematically in the equation of continuity. Under the heading of Mathematical Description of Space and Simple Media, the density functions defined for separate bodies and regions are interrelated, and the repulsion-attraction postulate is formulated. Succeeding topics are Transformations of Field and Force Equations, and Electromagnetic Waves in Unbounded Regions. An introduction is then given to the study of skin-effect and internal impedance, a study of boundary line problems and the solution of the homogeneous wave equation in cylindrical coordinates using Bessel function. The last part of the text proper is devoted to electric currents where the problem is formulated in general terms for configurations involving only conductors of small circular cross-section and condensers which have a dielectric that is so thin that edge effects are negligible. Also consideration is given to closed and quasi-closed circuits that are restricted in size so that all points are in the near zone with respect to each other.

The presentation is from a purely logical approach. In the back of the book there is a short outline of historical development of the science and appendixes of helpful information. The treatment is rigorous but plain. It is valuable to those in need of it.

R. H. OPPERMANN.

FIRE PROTECTION THROUGH MODERN BUILDING CODES, by B. L. Wood. 244 pages, 15 × 24 cms. New York, American Iron & Steel Institute, 1945.

The author of this book is a consulting engineer on the staff of American Iron and Steel Institute and has acquired a comprehensive knowledge of the many problems involved in the conception and application of building code regulations. Many of these regulations today do not reflect awareness of modern developments particularly with respect to fire protection; because there are so few opportunities available to become acquainted with them unless interest is directly in their path. This book has been written to assist in the rationalization and the modernization of fire protection regulations. It correlates the pertinent scientific data which have become available in recent years, so that clearer thinking in the preparation of fire protection regulations for building codes may be stimulated.

The work begins by referring to recent developments in fire protection and the use of the technical data on hand. An analysis is then made of hazards classified by occupancies and

buildings classified by occupancies. A clear statement of the objectives of building code regulations is given and discussed. Then there is a classification of buildinsg by types of construction and references made to restrictions, prevention of spread of fire by floor cut-offs, etc., fire resistance ratings of materials and constructions, and exit requirements. Appended are a set of Building Classification and Fire Protection Regulations. These are incidental to the discussions and illustrate a practical application of the principles covered. They were prepared as a part of the program of the Committee on Building Codes of the American Iron and Steel Institute.

This book should be used by all those having to do with the formulation of building codes. It makes for better and more up-to-date codes.

R. H. OPPERMANN.

ENGINEERING PREVIEW, by L. E. Grinter and others. 581 pages, illustrations, 16 × 24 cms. New York, The Macmillan Company, 1945. Price $4.50.

With the increasing percentage of population becoming intimately associated with engineering developments, there is a parallel interest of prospective students in this field of engineering. Perhaps the most frequently asked question by such students is, "Am I fitted to study in this field?" The best answer to this must be convincing to the student himself. In the preface of the book at hand it is stated,

> "Engineering Preview serves to orient the reader in the fields of science and engineering. . . . If you find this book tiresome and confusing, it is unlikely that you would want to become a technologist; but if it seems clear and stimulating, you are probably destined to use a slide rule."

The book is the work of seven authors, each writing in his own field. Each presentation is organized and connected with the others. The work starts out with the purpose of orientation which includes a simple self-scoring test which gives an inventory of the reader's technological traits. The science of matter and molecules is reviewed before the language of engineering, which is mechanical drawing, is taken up. A survey is made of mathematics as a universal tool of engineering and a treatment on the use of the slide rule is given. Then some of the basic engineering applications of physics are referred to, such as illumination, electric power, electronics, mechanics, heat engines, and refrigeration. These applications are from the engineering point of view rather than that of the physicist.

This work can be applied in the senior year of high school or the freshman year at college. But there is also another use to which the book can be put and that is for those of whom time has removed from the close acquaintance with scientific subjects, for this book is a means of refreshing knowledge of the various science and engineering fundamentals. It is interesting and impressive.

R. H. OPPERMANN.

ELECTRICAL COILS AND CONDUCTORS, by Herbert Bristol Dwight. 351 pages, illustrations, 14 × 22 cms. New York and London, McGraw-Hill Book Company, Inc., 1945. Price $5.00.

Electrical engineering requires a great many practical applications of formulas. Coils with and without iron coils constitute perhaps a majority of such work. From time to time there appears in the technical literature short-cuts in methods and brief clarification of theories that produce time saving and accuracy in application. This book refers to many of these references and connects them together with links of the author's own contributions.

There are thirty-nine chapters each dealing with a separate topic. Transformers are covered in the beginning. This deals with reactance of concentric core types, interleaved components, operation of delta and open delta transformer banks, and eddy-current losses. Other sections deal with reactance of rectangular conductors, skin effect, proximity effect, mutual inductance, magnetic field strength near a cylindrical coil, and magnetic forces. Although some of the characteristics of apparatus are presented in the form of curves and can be read without trouble, for most of the calculations a knowledge of the principles of

operation of the different types of electrical apparatus and a working knowledge of elementary integral calculus are needed.

The method of presentation is worthy of note. Descriptive matter almost similar to note-book style of a very direct type covers theories and curves, and the formulas are given as illustration. Many of them are worked out in practical examples. At the end of the book is a subject index.

The book is valuable as a reference work and time-saver. In many cases it would first be used by engineers as a refresher, for which it is ideal.

R. H. OPPERMANN.

EBULLIOMETRIC MEASUREMENTS, by W. Swietoslawski. 228 pages, illustrations, tables, 16 × 23 cms. New York, Reinhold Publishing Corporation, 1945. Price $4.00.

There have been ebulliometric apparatus in early stages and development since the early 1920's. In 1919 two papers appeared in the same issue of the *Journal of the American Chemical Society* in which two different pieces of such apparatus were described. Both were based on the same principle, and made it possible to measure exactly the real boiling temperature of liquids or solutions. The technique of precise determinations of boiling and condensation temperatures has recently advanced considerably, and can be measured with an accuracy of 0.001 to 0.0005° C. Both of these temperatures are measured to determine the purity of liquids, in examining the azeotropy of binary and ternary mixtures, in molecular weight work, in micro-analytical determinations of impurity contents, in studying the thermal resistivity of liquids, in tonometry, and in everyday analytical tasks. This book presents a comprehensive description of the method.

The work opens with a treatment of ebulliometric measurements, covering the apparatus and its functioning, its many forms, its sensitivity. The classification of liquid systems then is covered. This plays an essential role because the methods in measurement described are based entirely upon it. There is described how the effect of changes in pressure is overcome by comparative measurements. This avoids the use of correction factors. The work then is devoted to the technique applied to the various fields of usefulness including determination of purity, molecular weight, microebulliometric determination of moisture content, and solubility of solid substances. There is a list of references in the back, with a subject and author index.

Besides the many examples cited there are many other problems which can be investigated with the same method, not only in physics and physical chemistry but in everyday research. The book should go far in stimulating further development of ebulliometry.

R. H. OPPERMANN.

CALCIUM METALLURGY AND TECHNOLOGY, by C. L. Mantell and Charles Hardy. 148 pages, illustrations, 15 × 24 cms. New York, Reinhold Publishing Corporation, 1945. Price $3.50.

Over a twenty-year period, calcium has shown a consistent growth in usage and has become an important metallurgical raw material. It is not a tonnage product in itself, but relatively small amounts have a great effect on the properties of materials to which it is added. Its physical, chemical, and metallurgical properties have been insufficiently appreciated. Its ramified uses in industry have largely gone unnoticed.

The authors of this American Chemical Society Monograph have been associated with the calcium industry for two decades and include in this book much of their experimental work both in the laboratory and in the field. The treatment covers the properties and production of calcium, its industrial application, the alloy systems of calcium with other metals; the preparation of chromium, thorium, uranium and zirconium metal powders by the use of calcium; and calcium in the petroleum industry. There is much useful material in the form of tables and curves. Knowledge of the subject is obtained from a large number of references, digested and presented in a manner which is logical and informative.

R. H. OPPERMANN.

TRANSMISSION LINES, ANTENNAS AND WAVE GUIDES, by Ronold W. P. King, Harry R. Mimno, and Alexander H. Wing. 347 pages, drawings, 14 × 23 cms. New York and London, McGraw-Hill Book Company, Inc., 1945. Price $3.50.

This book was developed from the lecture notes of a special war time training course given at the Graduate School of Engineering, Harvard University, for officers of the Signal Corps who were graduate electrical engineers. It is therefore somewhat abbreviated and designed to emphasize essentials for immediate practical application. It also reflects in high degree the results of experience in methods of presentation for such a course.

There are four chapters, comprising the work. The first on transmission lines is concerned with the behavior of lines at radio frequencies, their use for the transmission of power, the use of short sections of line as reactances and for impedance matching, their use in the measurement of frequency, and the measurement of impedances at radio frequencies. Antennas, which is the heading of Chapter Two, opens with a qualitative introduction to general electromagnetic theory and proceeds through the topics of the driven antenna as a circuit element, coupled antennas and transmission lines, the receiving antenna as a circuit element, electromagnetic field of antennas and arrays, and closed circuits as antennas. The same general principles are applied in Chapter Three to circuits of a different type. Here, ultra-high frequency circuits are discussed, including the coaxial line, resonant and nonresonant circuits. The last chapter is devoted to wave propagation. This is somewhat brief. It brings out the essential facts governing ground-wave and sky-wave propagation, and relates these to well known scientific principles to show that the newly described phenomena are in reality wholly natural and understandable. This treatment is largely non-mathematical.

In the back of the book are problems for exercise, many of them with answers, and a subject index. There is a logical sequence to each treatment in the book. It should have considerable post-war use as a text and reference.

R. H. OPPERMANN.

PUBLICATIONS RECEIVED.

Studies in Biophysics: The Critical Temperature of Serum (56°), by Lecomte du Nouy. 185 pages, tables and illustrations, 15 × 23 cms. New York, Reinhold Publishing Corporation, 1945. Price $3.50.

Thermodynamic Properties of Air, Including Polytropic Functions, by Joseph H. Keenan and Joseph Kaye. 73 pages, 19 × 26 cms. New York, John Wiley & Sons, Inc., London, Chapman & Hall, Limited, 1945. Price $2.25.

Elementary Electric-Circuit Theory, by Richard H. Frazier. First Edition. 434 pages, illustrations, 14 × 22 cms. New York and London, McGraw-Hill Book Company, Inc., 1945. Price $4.00.

Industrial Oil and Fat Products, by Alton E. Bailey. 735 pages, tables, 15 × 24 cms. New York, Interscience Publishers, Inc. 1945. Price $10.00.

The Chemistry of Leather Manufacture, by George D. McLaughlin and Edwin R. Theis. 800 pages, tables and illustrations, 16 × 24 cms. New York, Reinhold Publishing Corporation, 1945. Price $10.00.

CURRENT TOPICS.

ARMY AND NAVY NOTES.

Crankshafts Polished to Less Than 2 Micro-inch.—(*Iron Age*, Vol. 155, No. 17.) Evolution of a new method of polishing aircraft engine crankshaft pins and bearings at Cadillac Motor Car Division has reduced surface finish roughness by more than 100 per cent besides effecting a saving of machines and space.

Previous to the installation of this new method, crankshafts had been lapped on a machine equipped with a 320-grit abrasive cloth to size the journals, eliminating taper and out-of-round conditions. The shaft was then moved to another lapping machine equipped with 400-grit waterproof-back paper and the journals given a finish polish. With difficulty, surfaces were held to tolerances in surface finish of between 4 and 5 micro-inch.

A general foreman of the Allison crankshaft department suggested that both lapping operations be performed without moving the crankshaft to another machine. Now, when the first polishing operation is completed, strips of the 400-grit polishing paper are laid over the crankshaft journals and under the 320-grit belts. They are adjusted so that a previously used section of the finer belt always is in contact with the shaft. The double thickness of belt, with the 400-grit paper against the shaft journals, then performs the final polishing operation.

The final polishing results in a profilometer reading of from $1\frac{1}{2}$ to $1\frac{3}{4}$ micro-inch—one of the finest surfaces ever produced in industrial practice.

R. H. O.

Oil Drums Buoy 1,700 Ft. of Pipe While Being Floated to Place.—(*Engineering News-Record*, Vol. 134, No. 16.) Empty oil drums, wire rope and a bulldozer were the principal items of equipment used at an advanced naval base in the Pacific for getting a water supply across a 1,700 ft. arm of the sea. The work was completed in two days by Seabees working under direction of Comdr. C. T. Wende, Seattle, Wash., who devised the program.

The available pipe, 4 in. in diameter, was in 20-ft. lengths with threaded connections. After the couplings had been screwed up tightly joints were welded for additional strength, making sure that welds covered all visible threads. The line was then pushed out with a bulldozer, aided by a wire rope from the forward end of the pipe that had been passed to the far shore for guiding and assisting in the pull. As the advancing end of the pipe reached the water's edge, beneath it were placed buoyancy units consisting of pairs of empty 50-gal. drums welded together to form a saddle or cradle in which the pipe could be supported. These pairs of drums were spaced at 60- to 80-ft. intervals.

When the pipe was all the way across the inlet a rowboat moved from one to another of the buoyancy units and a pick was used to make holes in both ends of each drum. This caused the buoyancy units to fill with water and sink slowly.

Special attention was required in the matter of anchorage to make the pipe secure against action of ocean currents. It was decided that concrete anchors were needed at four points and that it would be best if these could be attached to the pipe by chains. As water depths ranged up to 110 ft. there would be advantage of sinking the anchor with the pipeline, thus avoiding need for a diver. The plan used was to make anchors out of drums filled with concrete, attach these to the pipe with chains at the shore line and float the anchors out with the pipe, supporting the anchors on additional drums, which also were punctured at the time of sinking.

R. H. O.

Bomber Assemblies Tested in New Hangar.—(*Refrigerating Engineering*, Vol. 49 No. 4.) Details recently released on the new test hangar at Eglin Field Proving Grounds reveal that the air conditioned space is large enough to test for the first time whole bomber plane assemblies under controlled climatic conditions. Artificial temperatures can vary from −70° to 165° in the heavily insulated chamber measuring 200 ft. by 250 ft. by 70 ft.

The York Corporation designed the refrigeration system. Six centrifugal compressors with a combined capacity of 860 tons handle the cooling of the large hangar as well as a smaller adjoining chamber 80 ft. long in which aircraft engines can be tested. Half a million cu. ft. per min. of sub-zero air passes over cooling coils and is routed through ducts by 100-h.p. fans.

An additional refrigeration problem was some means of protection for observers working inside the hangar when the temperature approached 165°. The solution is tiny self-propelled cars enclosed in glass and carrying their own miniature air conditioning systems.

R. H. O.

Mosquito Control.—An ingenious and simple poisoning device that works automatically against certain types of vexatious mosquitoes does so by withholding a deadly dose of DDT until it is needed and then delivered at the time it will be most effective against newly hatched wigglers. The U. S. Department of Agriculture reports this from the Orlando, Fla., laboratory of the Bureau of Entomology and Plant Quarantine, which has been rushing research efforts for protection of the armed forces against insect pests and insect-carried diseases.

The device takes advantage of the fact, established by scientific studies of the life habits of the insects, that mosquitoes of the *Psorophora* group have the habit of laying their eggs in grassy areas that are likely later to be flooded by heavy rains or rising streams and ponds. The eggs mature, and as soon as the land is covered by water, they are ready to hatch almost instantly and soon develop into biting adults. One species is known as the shaggy-legged gallinipper; another is the Florida glade mosquito.

Hatching in enormous numbers, these biters may be a terrible pest to troops, farmers, and others working out-doors. Entomologists can inspect an area, locate the egg-infested soil, and predict that trouble will follow. But treating broad areas in the short time between flooding and the biting period has been difficult. The new development permits making preparations in advance of hatching.

The new device is a bottle containing a small quantity of DDT in oil. The bottle is partly buried in the soil in an area where hatching is likely. The bottle has an opening just above ground level. As soon as flood water rises to this opening the oil floats out and spreads a thin, deadly film to kill new hatched wigglers when they come to the surface.

DDT, however, is toxic to fish and other forms of aquatic life. The conditions under which the new device may be used still remain to be worked out. The Bureau also expects to test the device in salt marshes and areas subject to flooding against other species of mosquitoes having egg laying habits similar to those of the *Psorophora* group.

Except for allocations for experimentation, the entire output of DDT is still required for use by the armed forces and the material is not available for general or civilian use.

R. H. O.

New RCA Multiplex Radio Telegraph System Opens Eight Channels For Use by Single Transmitter.—Development of a system of word transmission by which eight channels can be employed simultaneously to carry messages thousands of miles over a single radiotelegraph transmitter has been announced by Lieut. Col. Thompson H. Mitchell, Vice President and General Manager of RCA Communications, Inc. The new system—regarded as a major advance in international communications—has been placed in operation between New York and London to increase communication capacity between the United States and Great Britain, and, with extension of channels to San Francisco, to expedite the flow of government and press traffic to and from the United Nations Conference.

By means of specially designed RCA equipment which employs what is known in the industry as "time division multiplex telegraph" principles, the equipment can handle 488 words per minute inward and outward simultaneously, corresponding to eight channels each way with an individual channel speed of 61 words per minute. The equipment also permits operation of four or two channels instead of eight channels, when desired.

All eight channels may be utilized for two-way communication with one distant station. Alternatively, they may be set up in such a way that four channels with a total capacity of 244 words per minute can be operated in both directions simultaneously between two different stations, with automatic retransmission of one or more of the channels to a third station.

Moreover, printing mechanism incorporated in the new RCA multiplex system accomplishes the feat of making the circuit virtually error-proof, despite its high speed. Let any letter be mutilated or garbled in transmission and a warning bell rings under the receiving printer. At the same instant, in lieu of the mutilated character, a Maltese cross appears to mark the exact spot of the error and facilitate correction. In other words, no error can get through directly to the message blank.

Vital to the system is a newly perfected method for keeping the receiving channelling devices in exact step with the distant transmitter and the signal elements being sent through the air.

En route to London, traffic from San Francisco passes through the synchronized equipment in the New York office of RCAC, at 66 Broad Street,

where the channels are separated automatically. Thence the messages flow, first, to the transmitting station at New Brunswick, then across the Atlantic. Routing from the British capital also includes passage through New York. Nevertheless, a mechanical delay of only one-sixth of a second occurs in the transmission in either direction.

It was pointed out that, while the system makes possible simultaneous transmission over four channels, each way between San Francisco and London through New York, the routing can be shifted, for instance, to send messages from either metropolis to the Argentine over the three-channel New York-Buenos Aires circuit.

R. H. O.

Peace Will Bring Pests.—Even after World War II ends this country will have to guard against foreign invaders in the form of dangerous plant pests. The alternative is a crop loss that could run to many billions of dollars every year. Immigrant plant pests are already here, and others may come on ships or planes, says the U. S. Department of Agriculture.

The fight has been on for many years and will be fiercer after the war, due to increased air traffic. During the war, air-borne commerce has increased tremendously. In one war year U. S. plant quarantine inspectors made more than 1,200 interceptions of foreign insects and plant diseases in airplanes—in baggage, cargo, mail, and stores.

Most of our very injurious crop pests and plant diseases came from abroad. They now cause crop losses estimated to total more than three billion dollars a year.

Last year a comparatively light infestation by a single pest, the European corn borer, caused a corn-crop loss of more than 22 million dollars. When weather conditions favor, even greater losses occur. This pest entered Canada and this country—probably on broom corn imported from Hungary and Italy—before plant quarantine inspection service was authorized in 1913. To reduce losses to his corn, a farmer must use extra time, labor, and often special machinery to destroy crop remnants after corn harvest.

Such a pest causes food loss and waste of farm labor, fertilizers and materials. Good land is overworked to make up production losses caused by pests.

Air-borne commerce after the war will provide opportunity for the entry of new pests, Federal entomologists say—pests that could not survive the longer period of steamer travel. Plant quarantine officials say that postwar air traffic is sure to require a constant battle to keep out immigrating pests.

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